rbit™ 1.8 Gaze Mechanics Simulation

User's Manual

1st Edition
September 1999

Orbit™ 1.8 Gaze Mechanics Simulation

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E i d a c t i c s
Visual Biosimulation

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Preliminaries

What is Orbit™?

The complexity of extraocular muscle coordination has long confused and frustrated students, researchers, and clinicians.

Orbit is a unique educational and research tool that provides easy access to a sophisticated biomechanical model able to simulate classical strabismus syndromes and data from individual cases, thereby clarifying diagnostic and treatment possibilities in well-defined physiologic terms.

Orbit is used all over the world:

- Ophthalmologists, Optometrists, and Orthoptists use Orbit to model complex cyclo-vertical and innervational disorders, refining diagnostic and treatment-planning skills.
- Researchers in vision and oculomotility use it to study orbital mechanics in humans and non-human primates, for instance, to distinguish orbital from central determinants of oculomotor phenomena.
- Teachers supplement the ophthalmology curriculum with self-paced strabismus simulation laboratories.
- Students working with Orbit are better able to consolidate loosely connected facts and observations into a solid sense of how the extraocular muscles work.

Orbit is a tool for analysis of extraocular mechanical and innervational factors in eye alignment. It contains a pair of *model eyes* you can modify to reflect supposed causes of motility disorders and proposed treatments, and a simulated *eye alignment test*, which shows how the modified eyes behave. Orbit is used to create models of extraocular disorders and treatments, observe their effects on eye alignment, and understand the reasons for those effects in well-defined biomechanical terms.

Orbit is used in a trial-and-error mode: Beginning with a pair of simulated normal eyes, you (1) alter one or both to reflect your ideas about diagnosis or treatment, (2) compare Orbit's simulated alignment with clinical alignment measurements or desired treatment outcome, (3) repeat until you're satisfied with the match. A Parameter Fitter helps refine the trial-and error process. Essentially, Orbit clarifies your hypotheses, shows you their implications, and provides a biomechanical analysis of your ideas. It does not replace your judgment and experience in proposing diagnoses and treatments.

In experimenting with diagnoses you can incorporate whatever you know or suspect: perhaps you know that you are dealing with a traumatic superior oblique muscle (SO) palsy, but are unsure of the degree of recovery and of secondary changes in other muscles. In experimenting with treatments you can allow for visual status, general medical status, lifestyle, etc. You are free to make the tradeoffs your experience suggests: Perhaps primary position is most important in one case and reading position in another.

Orbit's model eyes are *biomechanical:* they are modified by changing properties, such as innervations, globe dimensions, and muscle insertions, lengths, stiffnesses, and contractile forces. Thus, Orbit is related to the ophthalmotropes of Ruete (1845), Wundt (1862), and others, its main advantage being that its behavior is constrained only by knowledge of orbital mechanics, and not by the materials and mechanisms feasible in a physical model.

For each gaze angle, Orbit pursues iterative solutions involving extraocular connective tissues, and the innervations, paths, and tensions of all muscles in both eyes, according to equations given, in part, by Robinson (1975) and Miller and Robinson (1984).

Orbit is a Macintosh™ computer program, and has been designed to operate in the consistent, natural way typical of Macintosh programs.

Concerning Medical Use

Though based on the best data and analyses available, Orbit is not approved for and should not be relied on for decisions about patient care. Orbit is not intended to substitute for any established diagnostic or treatment planning procedure.

First, we are only beginning to understand extraocular muscle cooperation in terms compatible with the physical sciences, that is, on a biomechanical level. The field is just emerging from the "schools of thought" stage, where knowledge and practice are organized around prominent teachers, but little is understood in terms of generally accepted first principles (Kuhn, 1970). Second, orbital and brain physiology of a particular patient may differ from the normal population values in the model. Finally, Orbit has not been widely tested against actual patient data.

What is Orbit Not?

There are two other, fundamentally different types of models that have been used in strabismus analysis: *empirical generalizations*, and *expert systems*.

Orbit contains no pre-programmed demonstrations of syndromes (eg: Bregman, Ly and Galetta, 1991) and no tables of surgical dose-response relationships (eg: Parks, 1975). Such empirical generalizations are only useful in "typical situations", and do not help understand underlying mechanisms. Instead, Orbit can *produce* strabismus demonstrations, and *derive* dose-response relationships.

Orbit is not an expert system. An expert system is a model, not of the topics of interest themselves (innervations, muscles, etc), but of the inferences and judgments of human experts. One could create as many different strabismus expert systems as there are strabismus experts!

Indeed, Orbit knows nothing about strabismus, except insofar as strabismus can be modeled as failures of normal binocular coordination.

Is Orbit Difficult to Use?

Yes and no.

As a Macintosh program, Orbit is simple and easy to use. If you know a few other Mac programs, learning Orbit will be easy.

However, if you are new to biomechanical analysis, you may find it quite unlike your current approach to strabismus. Although you will not need to learn mechanics, mathematics, or anything not in this manual, you will need to sharpen your analytic thinking in several areas, as you will see.

Why bother? If you believe biomechanical analysis to be an academic exercise or passing fad, you will probably not want to make the effort necessary to understand this new approach. However, if you are concerned that strabismology in its current form may not be equal to coming technical, economic and competitive demands, you should waste no time in adding this new tool to your armamentarium. So far as we know, biomechanical modeling offers the only coherent, scientific approach to problems of eye alignment.

Conventions Used in this Manual

We will refer to items from the Menu Bar (at the top of the Macintosh screen) with the » symbol. For example:

» File » New	means move the cursor to the **File** item on the Menu Bar, then click and drag to select **New.**
» » About Orbit™	means move the cursor to the item on the Menu Bar, then click and drag to select **About Orbit™**.

In the Tutorial section of the manual, we use a pointing finger ☞ to indicate actions you should take to follow the example on your Macintosh.

The digital graphics in this Manual are in color, although printed copies are grayscale, for reasons of cost. Color PDF (Portable Document Format) files are provided on the Orbit CD-ROM (see below) and on our Website at www.eidactics.com/Software. Web editions will be updated, as indicated by fractional edition numbers (eg, 1.1).

PDF files can be viewed and printed with Adobe® Acrobat® Reader, provided on the Orbit CD-ROM, and also available online at www.adobe.com.

We Did Not Do This Alone

Development of Orbit's graphical interface has been supported in part by The Smith-Kettlewell Eye Research Institute, San Francisco, CA.

The underlying biomechanical model, and the physiologic research on which it is based continues to be supported by National Institutes of Health/ National Eye Institute grant EY06973 to JM Miller at Smith-Kettlewell, and EY08313 to JL Demer at Jules Stein Eye Institute, UCLA and JM Miller at Smith-Kettlewell.

For more about those involved in this project, launch the Orbit application and select » » **About Orbit™**.

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Macintosh, Power Macintosh, Mac, the MacOS logo, System 8, Balloon Help, and MacApp are trademarks of Apple Computer, Cupertino CA. Mac and the Mac OS logo are used under license.

Unix is a trademark of AT&T.

Required & Recommended

To run Orbit, we recommend a Power Macintosh™ computer (which use 601, 603, 603e, 604, 604e, 750 or G3, or G4 processors).

Orbit will run on a pre-PowerMac (sometimes called a "68K" Mac, because it uses a Motorola 68000 series processor) that has a math coprocessor and, at least, MacOS 7.5.5, but it will run very slowly (see page 115). We anticipate that the next version of Orbit will run only on PowerMacs.

If you are using MacOS 8.0 you must also install some system extensions that are included with the Orbit distribution materials -- see the Orbit 1.8 Release Notes. You may also install these extensions into MacOS 8.1, but must not install them into any other MacOS version.

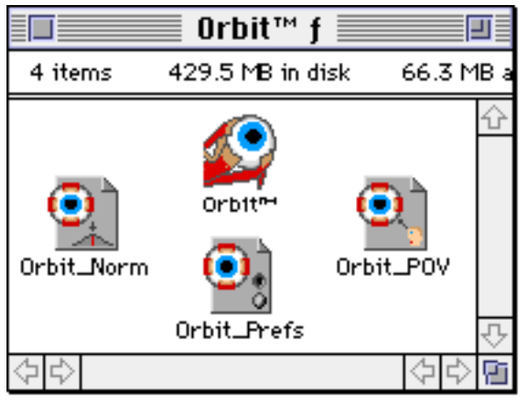
Your computer must have at least 8MB of RAM available to Orbit, and so at least 16 or 32 MB total, and at least 256 color graphics.

No Windows™ version of Orbit is available or planned. It is simply too difficult to support evolving software on multiple platforms.

This manual assumes that you know how to use a Macintosh. The Macintosh Tutorial, which came with your system, teaches basic Mac skills. Your Macintosh User's Manual, and Macintosh online **Help** can also be consulted about basic operations and terminology. This Manual also assumes that you know the basics of oculomotility and strabismus.

Installing & Registering Orbit

Orbit 1.8 cannot open simulations created with versions of Orbit older than 1.5. If you plan to work with older simulations, eg, keep your old version of Orbit. Be sure to keep these four files shown:



To install Orbit 1.8 on your computer:

☞ If you received Orbit on floppy diskettes, drag the contents of the 2 or 3 diskettes to your hard disk:

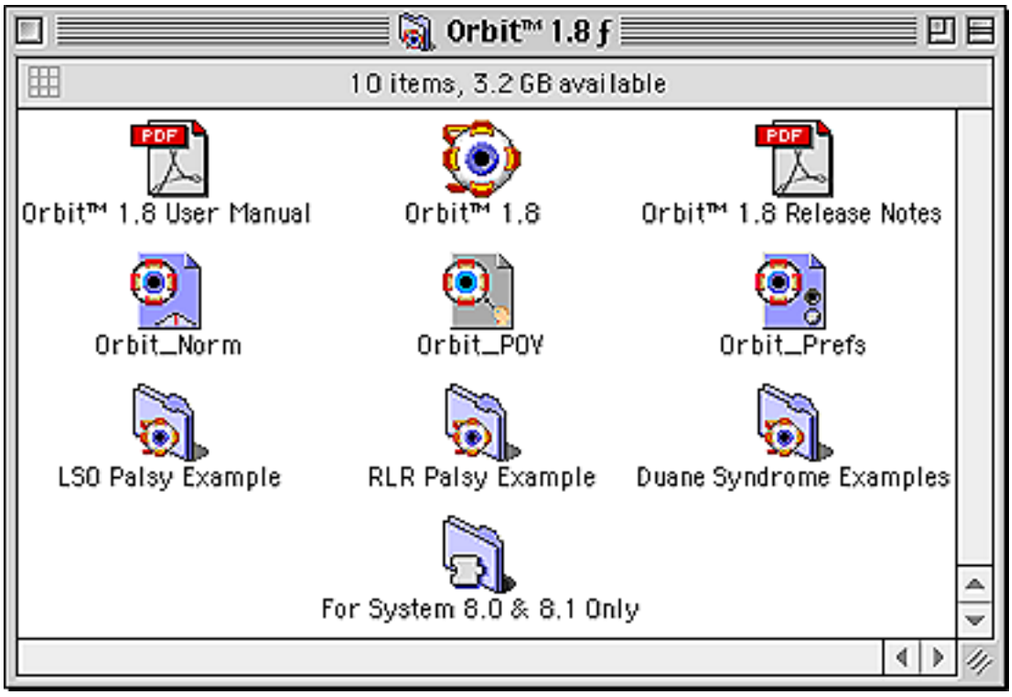
If you received Orbit over Internet, you will instead have a single archive file:

☞ In either case, double-click Orbit™ 1.8.sea to unpack the archive and get the Orbit™ 1.8 ƒ folder.

☞ If you received Orbit on a CD-ROM, simply drag the Orbit™ 1.8 ƒ folder from the CD-ROM to your hard disk.

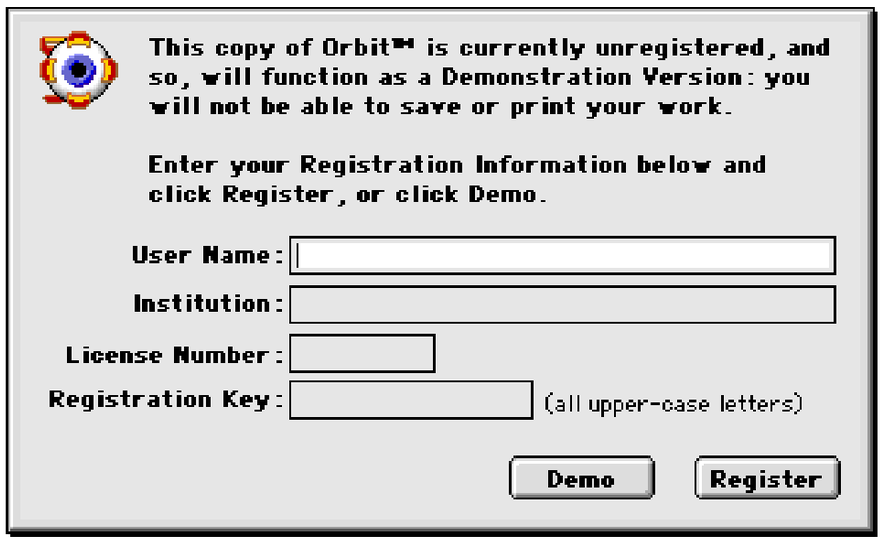
Orbit Installation Files

☞ Open the folder, and you should see something like this:

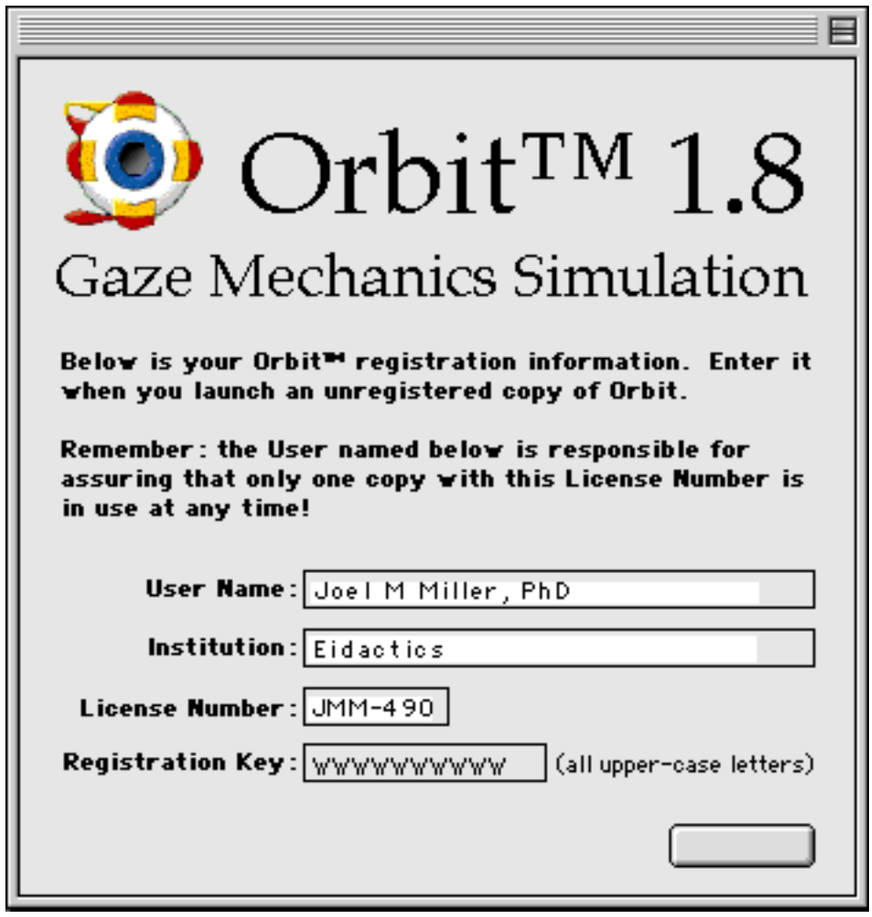


... is the Orbit program (*application* in Macintosh parlance). To run (*launch*) Orbit, you can double-click this icon, drop a *simulation file* on it, etc.

Whenever you launch an unregistered copy of Orbit, you have the option of entering registration information, or running in demonstration ("demo") mode. Orbit operates normally in demo mode, except that output functions (saving, exporting and printing) are disabled.


This copy of Orbit™ is currently unregistered, and so, will function as a Demonstration Version: you will not be able to save or print your work.
Enter your Registration Information below and click Register, or click Demo.
User Name:
Institution:
License Number:
Registration Key:
(all upper-case letters)
Demo
Register

If you have purchased an Orbit license (see the Order Form & License Agreement near the back of this Manual), you will have received a card containing your registration information:


Orbit™ 1.8
Gaze Mechanics Simulation
Below is your Orbit™ registration information. Enter it when you launch an unregistered copy of Orbit.
Remember: the User named below is responsible for assuring that only one copy with this License Number is in use at any time!
User Name: Joel M Miller, PhD
Institution: Eidactics
License Number: JMM-490
Registration Key: WWWWWWWWW
(all upper-case letters)

Enter all four lines as shown on the card. The registration key is always exactly 10 upper-case English letters. If you misplace your registration information, we can provide it from our files.

... is a description of improvements in, and limitations of, the new version. Adobe Acrobat Reader 3 or better (provided on CD-ROM, and available free from Adobe at www.adobe.com) is needed to read it.

The following 3 files are used by Orbit. Most users will not deal with them directly. Be sure to keep them together with Orbit in the same folder.

... is the standard set of normal eye parameters used by Orbit. When Orbit is launched, Orbit_Norm is read in as the description of normal eyes. When a new simulation is created, parameters from Orbit_Norm are

stored as starting values in the new document. Factory Settings for all Preferences are also stored in this file (this allows you to return to these standard settings, whenever you wish).

It is possible for knowledgeable users to modify Orbit_Norm (it is a plain text file) to incorporate new data about normal eye mechanics, or create versions for different ages, races, sexes, and species. (If you do this, be careful to only change values of existing parameters, or add comment lines). If you alter Orbit_Norm, or replace it with a new version, remember that only newly created simulations will reflect the change. Existing simulations that are opened or modified will not. Orbit will complain when it is launched if it does not find Orbit_Norm in its folder.

... stores your Preferences for New Simulations, that is, the settings you make (as explained below) to customize the way Orbit creates new simulations (it initially stores standard Factory Settings). You can create different sets of preferences for different users: simply swap the desired Orbit_Prefs into Orbit's folder. If there is no Orbit_Prefs file in its folder, Orbit will create one with Factory Settings.

Orbit_Prefs also stores your registration information. If you wish to give a copy of Orbit to a colleague, give him or her everything in this folder except for Orbit_Prefs.

... holds Point of View settings (discussed below). If there is no Orbit_POV file, Orbit's Point of View window will not show named points of view.

... contains items you may need to put into your System Folder. If you are using MacOS 8.0 or 8.1, open this folder and drop the contents onto your closed **System Folder**. Let the Finder put the three items contained in their proper places. Then restart your computer and launch Orbit again. Do not install these items into any system version other than 8.0 or 8.1.

Other files and folders in Orbit™ 1.8 ƒ contain simulations of strabismic disorders, and related files, some of which are referred to later in this manual.

Adobe Reader is needed to read the digital version of this Manual, and the Orbit Release Notes. We include the 4.0 installation kit on the CD_ROM, because earlier versions seem to crash MacOS 8. For the current version of Adobe Reader, see www.adobe.com.

If Orbit complains that your computer does not have necessary hardware or software, then either your MacOS System version is too old (remember: Orbit has been tested only with MacOS 7.5.5 and later; you may be able to upgrade your OS), or your computer is inadequate. Some old Macs (eg, MacIIsi) may not have math coprocessors, and cannot run Orbit.

As you work with Orbit, you will create new *simulation files* (the generic Macintosh term for which is *documents*); you may put these anywhere (Orbit Demo does not allow simulations to be saved).

Cleaning Up

☞ The archive file or files (Orbit™ 1.8.sea...) you may have are no longer needed. Drag them to the Trash to complete the installation.

☞ If the various Orbit files do not have their icons, shown below, or if double-clicking an Orbit simulation fails to open it with Orbit, you must rebuild your Macintosh desktop. To do this, restart your Mac, while holding down the Command and Option keys.

Sharing Orbit with your Colleagues

As an Orbit licensee, you are free to share Orbit with your colleagues, within the terms of your License Agreement.

Each license allows one simultaneous use of Orbit. This means that you may install and register Orbit on several machines (eg, an office and a home computer) or on a single machine for use by several people, provided that all installations are under your control, in that you can ensure that only one copy is in use at any time.

You may also distribute copies of Orbit that will not be under your control, but in this case you must not share your registration key or the Orbit file (see below) that contains an (encrypted) key that you previously entered. Your registration key is the 10 letter code shown on the last line of your Registration Information Card (pictured a few pages back). You may:

Loan your distribution media (CD-ROM, floppy disks or downloaded archive, but not your Registration Information Card, which may have been included with the distribution media).

Copy all the files from the folder

, except for the file

. Orbit_Prefs stores the registration information you entered from your Registration Card, as described above. Distributing it would violate your license agreement.

Download the latest version of Orbit from our Website: www.eidactics.com/Software. Such shared and downloaded copies are fully functional, except that output functions are disabled. To enable output functions for a new, independent user, a new Orbit License must be purchased.

Please be mindful of the difficulty maintaining software as complex as Orbit for our small, specialized market. By honoring your license agreement you help make possible ongoing development and maintenance of Orbit.

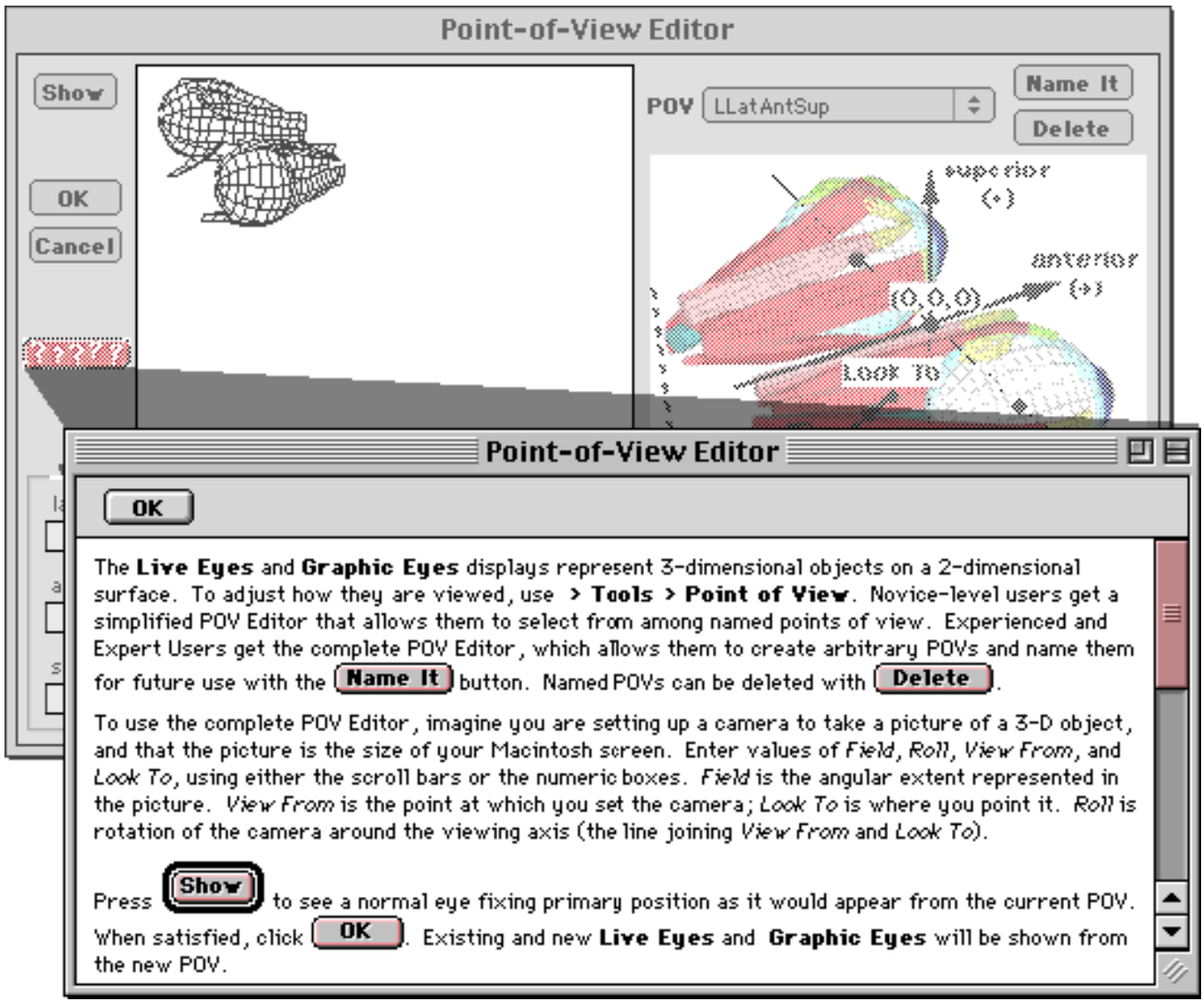
Click for Help

Helpful information embedded in a program is particularly useful: it is there when you need it, and can be *context sensitive*: you don't have to search for the topic you're having a problem with, because the program knows where you are.

Orbit provides three kinds of help.

Window Help Buttons

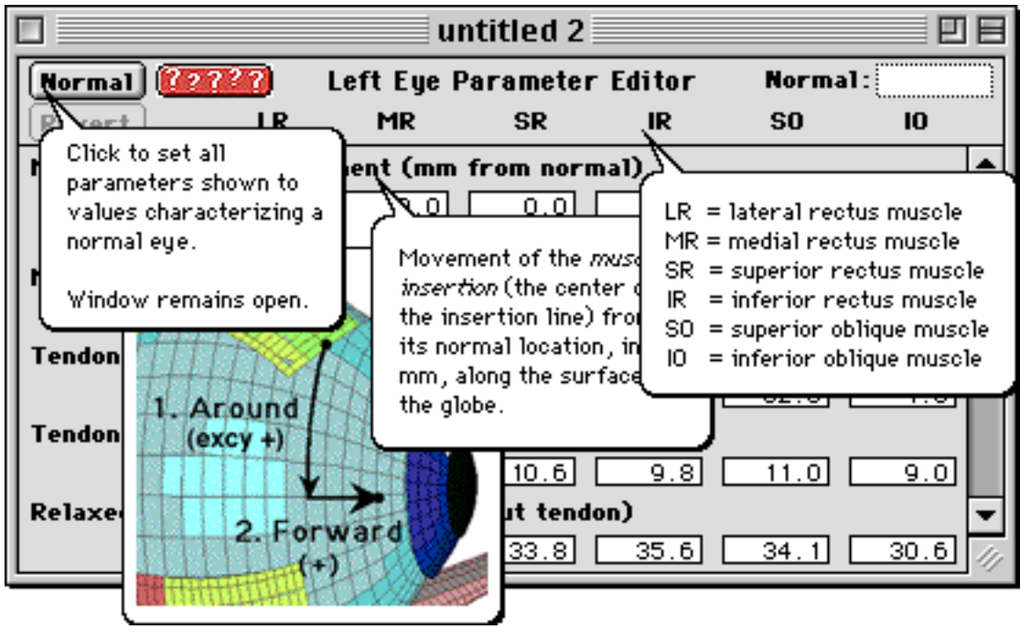
Many Orbit windows contain a *help button*. Click it for a description of the window.

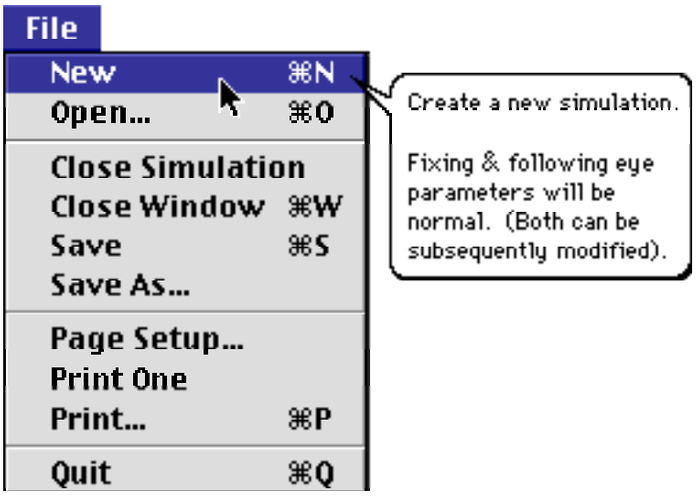

Point-of-View Editor
Show
OK
Cancel
POV
LLatAntSup
Name It
Delete
superior
(+)
anterior
(+)
(0,0,0)
Look To
Point-of-View Editor
OK
The Live Eyes and Graphic Eyes displays represent 3-dimensional objects on a 2-dimensional surface. To adjust how they are viewed, use > Tools > Point of View. Novice-level users get a simplified POV Editor that allows them to select from among named points of view. Experienced and Expert Users get the complete POV Editor, which allows them to create arbitrary POVs and name them for future use with the Name It button. Named POVs can be deleted with Delete.
To use the complete POV Editor, imagine you are setting up a camera to take a picture of a 3-D object, and that the picture is the size of your Macintosh screen. Enter values of Field, Roll, View From, and Look To, using either the scroll bars or the numeric boxes. Field is the angular extent represented in the picture. View From is the point at which you set the camera; Look To is where you point it. Roll is rotation of the camera around the viewing axis (the line joining View From and Look To).
Press Show to see a normal eye fixing primary position as it would appear from the current POV. When satisfied, click OK. Existing and new Live Eyes and Graphic Eyes will be shown from the new POV.

Balloon Help™

Balloon Help lets you point to an object on the screen to find out what it is.

☞ To turn on Balloon Help, select **» Help » Show Balloons**. Then, point to an object in the menu bar or in an Orbit window (titles, labels, buttons, ...) to find out what it is and how to use it.





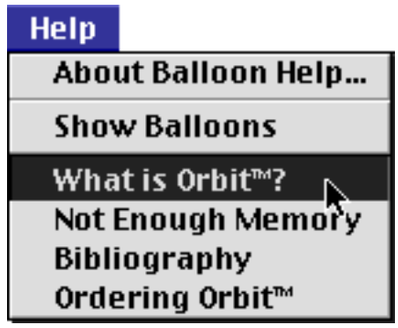
Orbit help balloons tell about strabismus and bio-mechanical modeling, as well as about using Orbit.

Turn Balloon Help on when you first use a window, and when you do not understand a menu selection, window, field or button. Then turn it off.

Help

Help on the Menu Bar

When Orbit is active, several short discussions are available online by clicking **Help** in the Menu Bar at the top of your Macintosh screen:



» Help » What is Orbit™? contains an overview.

» Help » Not Enough Memory suggests things to try when Orbit (or any other Macintosh application) makes this complaint.

» Help » Bibliography. An annotated bibliography of scientific papers in which the biomechanical model underlying Orbit, the basic research supporting the model, and some clinical applications are discussed.

» Help » Ordering Orbit™ tells how to purchase Eidactics products.

A Biomechanical Approach to Strabismus

Clarification is one of the aims of our biomechanical approach, so it would be ironic if a mysterious physiologic system were simply replaced by a mysterious computer program. It is important to understand something about the foundation and inner workings of Orbit.

The most important thing for you as a user to know is what is included in Orbit's calculations and what is not. A biomechanical model such as Orbit is "minimalist" in the sense that it does automatically only those calculations that necessarily follow from specified variables and parameters. Effects that may occur in only some cases, or for which there is no clear mechanism, cannot and should not be automatically computed. Instead, Orbit allows you to explicitly test hypotheses about such effects.

Orbit includes models of:

- *muscle force* (including elastic and contractile force components),
- *muscle path* (including muscle length),
- *Hering's Law*, which determines innervations to an eye moving "passively" or "under cover", given the position of the fixing eye and the parameters of both.
- *Sherrington's Law of reciprocal innervation*, which relates innervations to paired antagonistic muscles.

Orbit does not include any models of central or peripheral adaptive processes, or of post-surgical healing. However, you can make hypotheses about these processes, express them in Orbit's biomechanical parameters, and derive their implications. Similarly, it cannot know the details of surgical technique (eg, how much tendon is lost in muscle recession), but you can express your estimates in terms of Orbit parameters.

Robinson (1975) and Miller and Robinson (1984) describe the mathematical analysis on which Orbit is based. This framework is fleshed-out with data on

extraocular geometry, muscle paths, muscle cross-sections, muscle forces, and elasticities.

We use a description of normal orbital geometry derived from dissections of Volkmann (1869), serial sections by Nakagawa (1965), and MRI studies by Clark (Clark, et al, 1997). Muscle paths and cross-sections are derived from MRI studies of Miller, Demer, and colleagues (Miller, 1989; Miller, et al, 1993; Demer, et al, 1994; Demer and Miller, 1995).

Parameters and Variables

We will use the term *parameters* or *eye parameters* to refer to values that characterize an eye and do not change as a function of eye position. A muscle's origin, stiffness and resting length are all eye parameters.

All other Orbit values, which can vary as a function of eye position, are *variables.* Elastic muscle force and muscle path length are examples of variables. Note, eg, that stiffness (change in force / fractional change in length), is an independent, intrinsic muscle property, that is, a parameter, whereas elastic force, a variable, depends on stiffness, muscle resting length and muscle path length. The length of the path over which a muscle travels depends on the shape of the path, which depends on eye position, total muscle force and pulley stiffness, among other things.

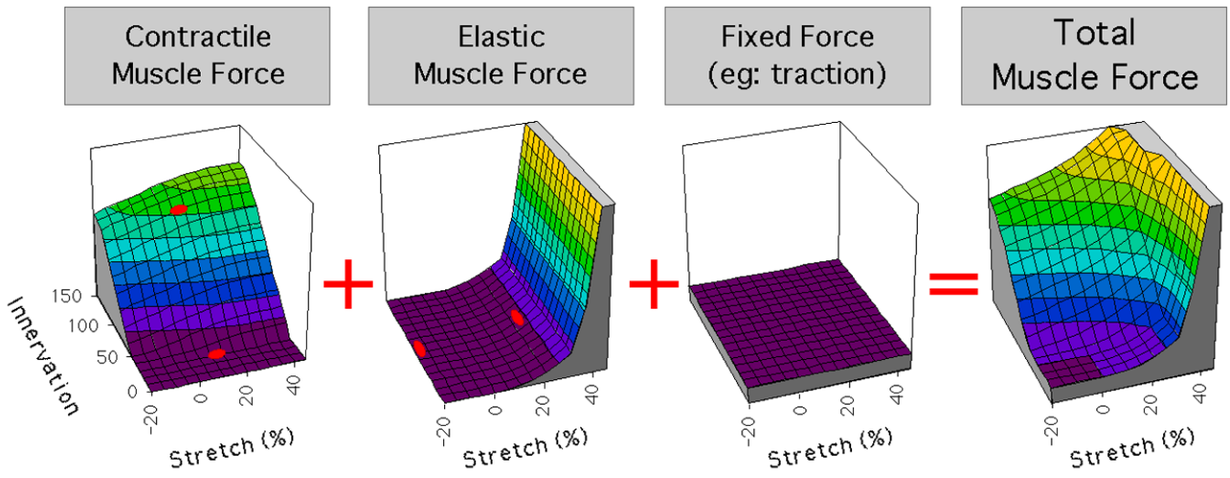
Fixing and Following Eyes

We use *eye alignment* and *binocular alignment* to refer to phoria, not tropia. This follows from the fact that Orbit treats biomechanical factors only, and knows nothing about such sensory factors as fusional range. Thus, when we talk about alignment, you should imagine some test of eye alignment that completely dissociates the two eyes in the sense of providing no binocular visual alignment cues.

It is essential to know which eye is the *fixing eye*, the eye voluntarily turned by the subject to point in a known direction, and which eye is the *following eye*, the eye which is moving under the influence of innervations determined by the fixing eye, "passively" or "under cover". The Hess and Lancaster tests approximate this ideal situation.

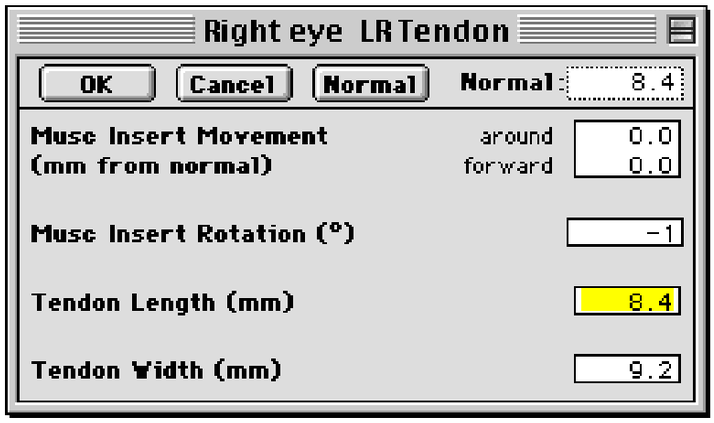
Muscle Force Model

Muscle force is calculated as the sum of a *contractile force*, an *elastic force,* and a *fixed force* (useful in simulating *traction tests*, in which an eye is rotated with forceps). Contractile force is mainly a function of *innervation*, but is also a function of fractional length change or *stretch*, consistent with the sliding filament model. Elastic force is a function only of stretch.



Consider a "simple" muscle resection. The mechanics of this common procedure are more complex than you may think, but since Orbit understands how eye muscles work, much of the complexity is taken care of automatically. To simulate resection correctly, you need to know what happens automatically and what is left to your judgment.

A modest resection may only remove tendon.



To perform a 5mm RLR resection, you would change the Tendon Length from 8.4, shown above, to 3.4. What are the mechanical implications?

First consider the operated eye fixing. When the operated eye is fixing a given position, say, primary position, the RLR will be more stretched than it was before surgery. Orbit computes the increased stretch,

increased elastic, and altered contractile force components of the RLR. It then computes the forces in the antagonist RMR and other muscles of the right eye needed to hold the eye in primary position, and the innervations needed to produce the contractile components of these forces. Having computed right eye innervations, Orbit uses its notion of Hering's Law to compute innervations to the following left eye, left eye muscle forces, and, finally, left eye position.

With the operated right eye following, innervations, determined by the unoperated fixing eye, are assumed unchanged from before surgery. Resection alters RLR forces, and so the right eye's position. Orbit calculates the new forces and eye position, as well as more subtle things, such as changes in muscle path shape and translational globe position.

Note that if you disinsert a muscle, cut off 5mm, and sew it back to the original scleral insertion, Orbit cannot know that you lost 1mm during disinsertion and took a 1mm "bite" of the remaining tendon during reinsertion. In this case, you actually did a 7mm resection, and must reduce Tendon Length from 8.4 to 1.4 mm.

Now, suppose we resect more than the tendon length, shorten the muscle proper.

Elastic Force ("stiff" vs "soft")

Resection shortens a muscle, and a short muscle is said to be "stiff". What does this mean?

Imagine taking a 10 mm rubber band (resting length = 10 mm), and extending it by 10 mm (path length = 20 mm; fractional stretch = (20 - 10) / 10 = 100%). Then cut off half of the band (resting length = 5 mm) and again extend it by 10 mm (stretch = (15 - 5) / 5 = 200%). It's harder to hold extended now because fractional stretch is higher. Each unit length of the band is now stretched to 3 times its resting length, compared to 2 times before it was cut.

Cutting a piece off the band did not change its intrinsic properties – the band is still made of the same rubber material and has the same cross-section. Similarly, the intrinsic stiffness of a muscle is determined by the nature of the elastic properties of the tissue (eg, its fibrous content) and its cross-section, and is measured in grams/fractional stretch. Cutting off a piece of

muscle, changing its resting length, only changes the fractional stretch of the muscle (eg, from 100% to 200%) for a given absolute movement of its end (eg, 10 mm), thereby changing its elastic force.

We describe elastic muscle stiffness in terms of fractional or percent change in length because then stiffness is an independent parameter, not dependent on resting muscle length. If we instead defined muscle stiffness in terms of absolute stretch (mm), it would change with resection. So, when one says, "a short muscle is stiff" one is using a different meaning of stiffness than we do here. We would say instead that a short muscle must be stretched more than a long muscle to cover the same path, and so, exerts more elastic force.

Orbit can also be used to simulate and test your hypotheses about changes in muscle cross-section (eg, hypertrophy or atrophy) or tissue properties (eg, fibrosis), which may occur over time in a resected muscle or its antagonist. Such "secondary" changes cannot be calculated automatically, however, because they are not, so far as we know, necessary consequences of resection and, in any case, little is known about their determinants. Orbit simulation is currently the only practical way to test such clinical and scientific hypotheses.

Contractile Force ("strong" vs "weak")

Contractile force depends mostly on innervation, which causes each sarcomere (one of the serial contractile elements of a muscle fiber) to shorten. There is also a length dependency intrinsic to the sarcomeres: they have an optimal length for force generation. Stretched or crushed sarcomeres develop less force at given innervations. The contractile force model built into Orbit automatically reflects these effects.

Orbit also provides parameters with which you can alter each muscle's response to a given level of innervation.

Orbit does not, for reasons that should now be clear, automatically calculate central innervational adaptations that might follow from strabismic lesions or muscle manipulations. This makes it a useful tool for testing hypotheses about such adaptational mechanisms.

In summary, removing a length of muscle affects both elastic and contractile components of muscle force:

- A resected muscle exerts more elastic force at a given length, and so, roughly speaking, at a given eye position. This effect is most significant when the muscle is elongated, that is, out of the muscle's "field of action". It is in this sense only that a resected muscle is "stronger".
- Resection of a muscle that removes contractile tissue leaves the muscle less effective in contracting. A given change in innervation results in less change in path length, and the range of lengths over which the muscle can effectively operate (recall the sliding filament model) is reduced. These contractile effects are most important in a muscle's field of action.

So, with respect to the above discussed effects of muscle manipulation, you specify the surgery (and any muscle abnormalities), and Orbit does the rest.

Secondary Effects of Surgery

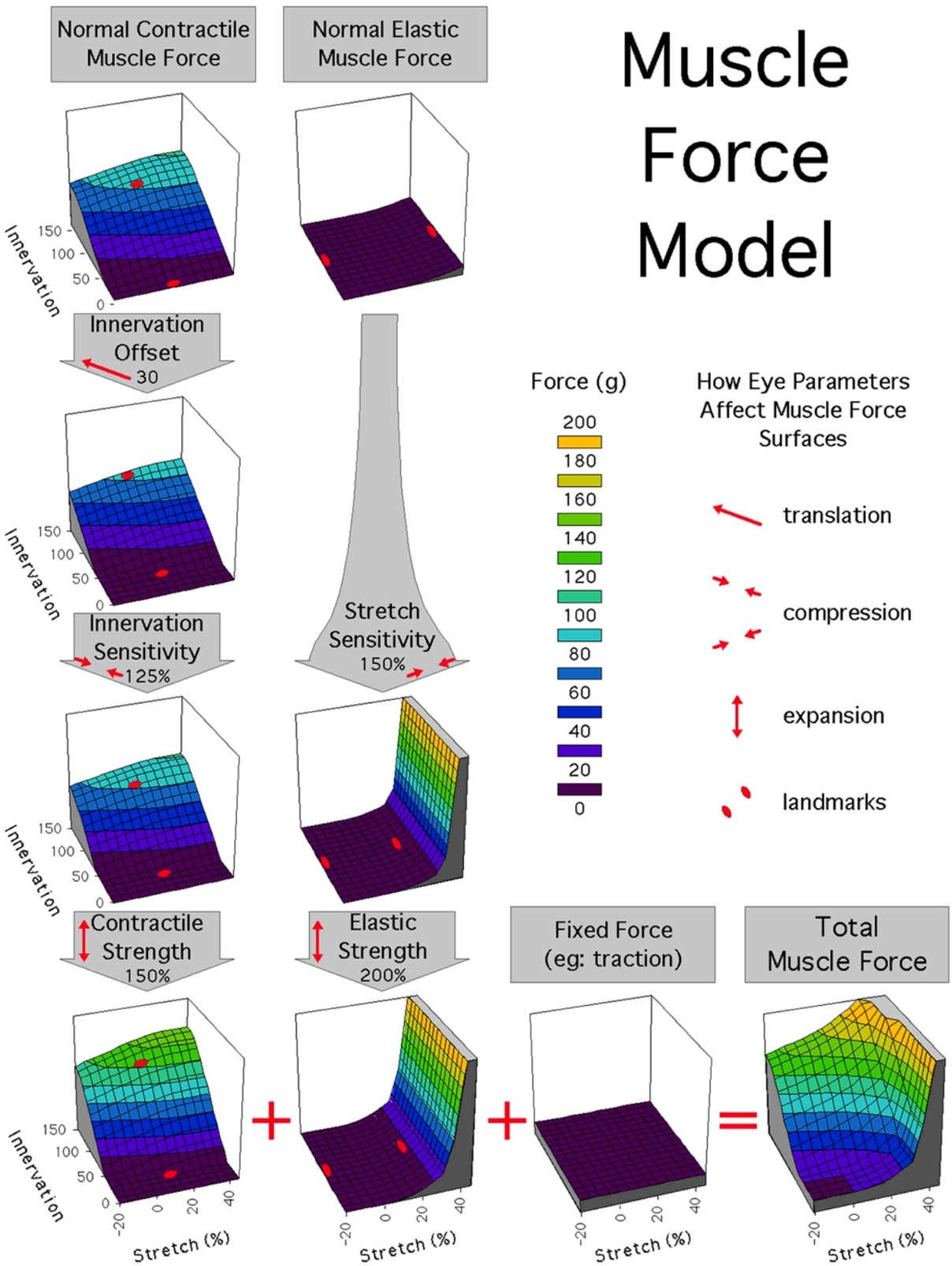
As we have seen, resection stretches a muscle, forcing its sarcomeres to operate at longer than optimal lengths. Conversely, recession slackens a muscle, forcing its sarcomeres to operate at shorter than optimal lengths. It has been found that, within a few weeks or months, resected muscles actually add sarcomeres, and recessed muscles delete sarcomeres, thereby allowing the remaining serial sarcomeres to operate at their optimal lengths (Tabary, et al, 1972; Williams and Goldspink, 1973; Williams and Goldspink, 1978; Scott, 1994).

However, muscle length adaptation is not well enough understood to be incorporated as automatic Orbit calculations. To predict long-term eye alignment, you must make your own hypotheses about such secondary muscle length changes, and enter your estimates into Orbit. In the Tutorial section, below, we will show how this might be done.

Even less is known about post-surgical modifications of innervation and about fibrotic and atrophic changes that may occur in some situations. As with secondary muscle length changes, you can enter any such changes you suspect, and Orbit will deduce their consequences.

Manipulating the Muscle Model

To simulate abnormalities, treatments, and effects of healing, Orbit allows you to alter *parameters* of the muscle model. Various scaling and offset operations on the normal force surfaces are available:



Innervation threshold (called *offset* in the figure), *innervation sensitivity* and *contractile (muscle) strength* allow the *normal contractile muscle force* surface to be customized.

- *Innervation threshold* slides the contractile force surface along the innervation axis, so that, eg, contractile force first appears at lower innervations for decreased thresholds, and saturates at innervations the same amount lower. Eg, if you have reason to think that neuromuscular junctions are weakened, increase innervation threshold.

  For a simple example, change the innervation threshold of a muscle in the following eye (Expert Parameter Editor) and note (in the Mechanical State Viewer) that innervation does not change (ie, the sensitivity of the muscle is affected, not the brainstem's output), but the *contractile muscle force* does change.

- *Innervation sensitivity* squashes (or stretches) the muscle force surface along the innervation axis, so every change in innervation behaves like a larger (or smaller) change on the normal surface. Myasthenia, eg, might be modeled by decreasing innervation sensitivity.

- *Contractile muscle strength* scales the vertical (force) axis. A large muscle with more contractile fibers in parallel than normal would be modeled by increasing contractile muscle strength.

  Expert note: Your Parameter Editor shows Contractile Muscle Strength and Contractile Muscle Relative Strength. Normally, the former values are all 100%, and the later give contractile forces relative to the lateral rectus muscle (LR). The two "strengths" are separated so you can think about changes with respect to either a muscle's normal strength alone, or relative to other muscles. Internally, the two values are simply multiplied, so, eg, doubling either has the same effect.

Stretch sensitivity and *elastic strength* allow the *normal elastic muscle force* surface to be customized.

- Stretch Sensitivity squashes the Elastic Force Surface along the stretch axis. A fibrotic muscle, which hits asymptotic stiffness (the *leash region*) at low values of stretch, would be modeled by increasing Stretch Sensitivity.

- Elastic Strength scales the vertical (force) axis. A large muscle with more elastic fibers in parallel than normal would be modeled by increasing elastic muscle strength.

  Expert note: Your Parameter Editor shows Elastic Muscle Strength and Elastic Muscle Relative Strength. Normally, the former values are all 100%, and the latter give elastic forces relative to the LR. The two "strengths" are separated so you can think about changes with respect to either a muscle's normal strength alone, or relative to other muscles. Internally, the two values are simply multiplied, so, eg, doubling either has the same effect.

The values of muscle forces and the rotational stiffness of non-muscular orbital tissues are derived from intraoperative and other measurements of Collins, et al (1975; 1981).

Translational stiffness of the globe, important in simulating restrictive and co-contractive syndromes, is estimated from the data of Dyer and Henderson (1958).

Hering's Law of Equal Innervation is simulated by converting innervation sets of the fixing eye into equivalent (with respect to a normal eye) gaze angles, reflecting the gaze angles across the midline, and converting back into innervation sets. This procedure is schematized in the *Test of Binocular Alignment* section below.

Sherrington's Law of Reciprocal Innervation is hard-coded, as described by Robinson (1975). It may be possible, in a future version of Orbit, to solve for each of the 6 innervations in a set independently, thereby simulating, rather than assuming, the exact form of reciprocal innervation.

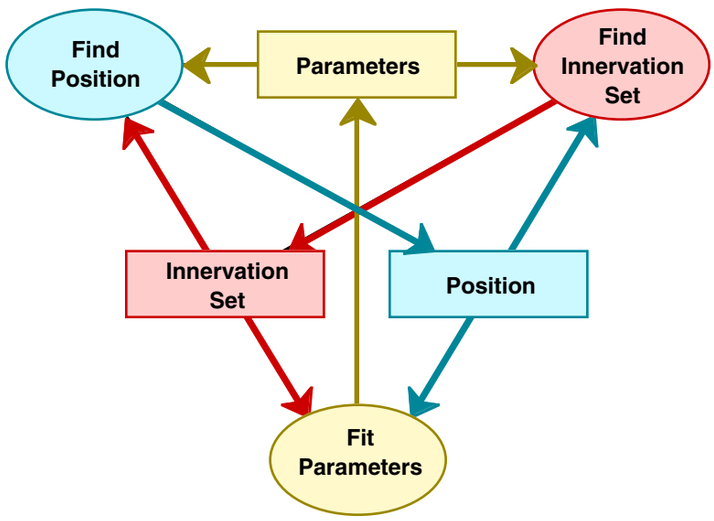
Basic Data and Operations

Orbit operates on three types of data: *innervations*, gaze *positions*, and eye *parameters*, solving a force-balance equation to determine innervations from positions and parameters, or positions from innervations and parameters. These two types of solutions answer two types of questions:

(1) What innervation set is required to drive a given eye to a given position?

(2) To where will a given eye move if supplied with a given innervation set?

Eye parameters include locations of muscle origins and insertions, muscle and tendon dimensions, innervation-length-tension relationships, and elastic properties of ocular fat and fascia. Innervations to the six muscles of each eye are given in arbitrary units. All three components of eye rotation are specified: abduction, supraduction, and excyclotorsion. Eye translation, significant in some disorders, is calculated as well.



Finding innervations and positions is relatively straightforward. However, clinical application needs the ability to *find eye parameters*. Finding eye parameters corresponds to making a *diagnosis* or *choosing a treatment*. Finding the parameters of eyes that show a given pattern of misalignment, or how eye parameters must be altered to restore good alignment is a trial-and-error process.

New in Orbit 1.8 is the Parameter Fitter, which automates the trial-and-error process. In some cases, then, Orbit 1.8 can also answer the third question:

(3) What parameters describe eyes that will move to desired positions under given innervations?

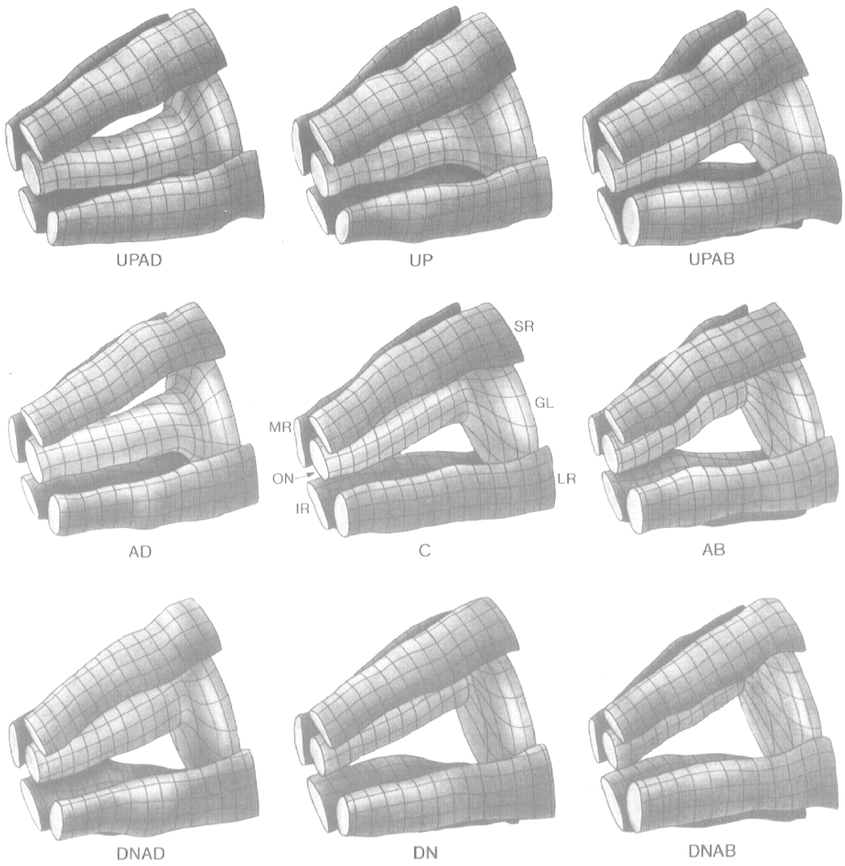
Rectus Muscle Pulleys?

In the Orbit 1.8 model rectus muscles pass through pulleys, located posterior to the equator, and elastically coupled to the orbital wall. *Soft rectus muscle pulleys* are a recent discovery, and since one might reasonably be skeptical about claims of new, functionally significant, gross anatomic structures in such a familiar part of the body, we will review the findings.

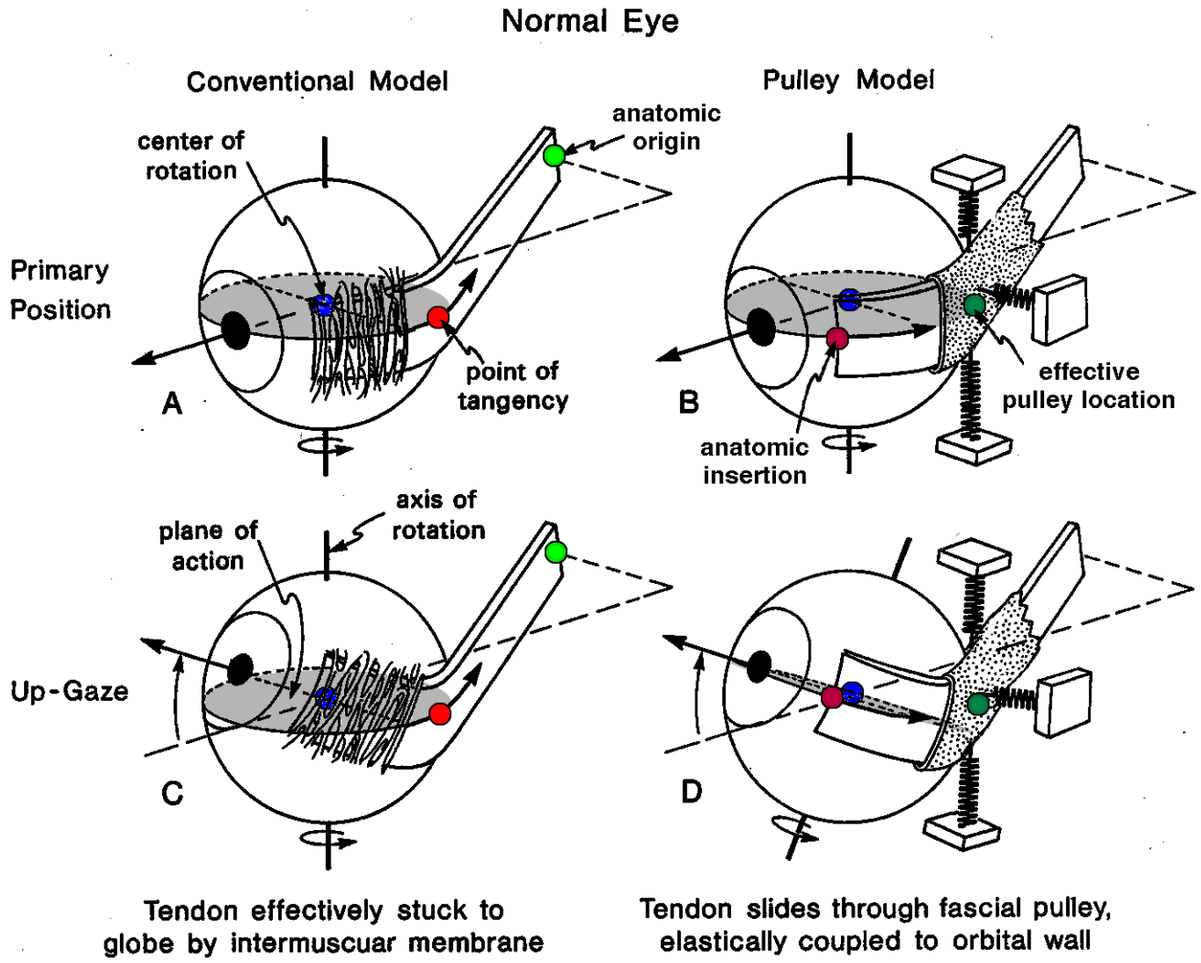
Prior to the development of computational models of extraocular biomechanics it seemed sufficient to describe extraocular anatomy in terms of origins, insertions, and cross-sections of extraocular muscles measured in cadavers. But then several new results appeared:

1. **Modeling:** The attempt to calculate binocular alignment from first principles (Robinson, 1975; Miller and Robinson, 1984; Miller, et al, 1984) made it obvious that paths of EOMs and gaze dependence of their paths could not be inferred from cadaveric data, but had to be measured in alert subjects.

2. **Imaging:** These measurements were performed in monkeys and humans by Miller, et al (1984), Simonsz, et al (1985), Miller and Robins (1987), and Miller (1989). The main finding of all these studies was that rectus muscle bellies are remarkably stable with respect to the orbital wall over the full range of gaze.

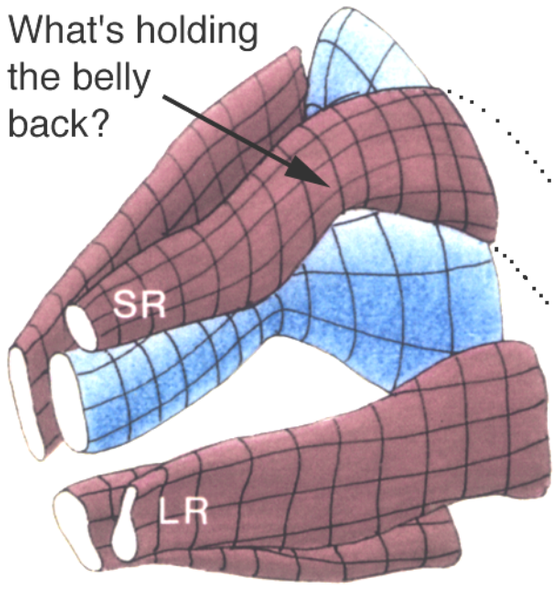


3. **More modeling:** We consider two distinct (though not mutually-exclusive) mechanisms to explain the observed path stability: one mechanism supposed connective tissue to couple an anterior extent of each muscle to the globe; the other supposed each muscle to pass through some sort of pulley coupled to the orbital wall (Miller, et al, 1984; Miller, et al, 1990; Miller and Demer, 1992). Simonsz ("personal" communication) has also emphasized the distinction between muscle paths *per se* and the path-determining mechanism.



Orbit 1.0 was based on the first notion, the *conventional model*. Many strabismus syndromes were well simulated by Orbit 1.0. However, simulations of muscle transposition surgery failed because Orbit 1.0 assumed that EOM bellies could sideslip in the orbit to follow transposed insertions (Miller, 1985).

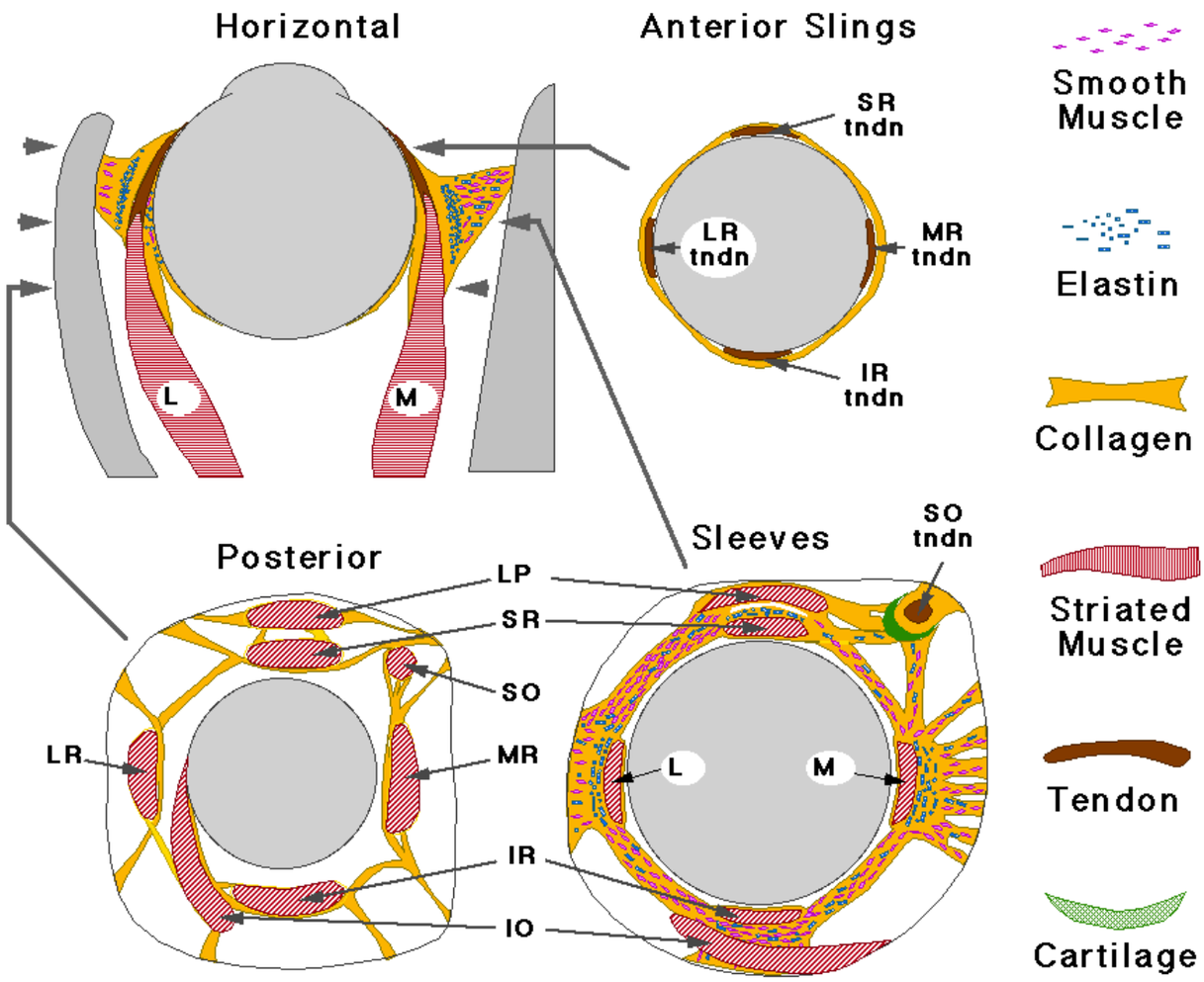
4. **MRI study of muscle transposition:** We reasoned that under the *conventional model*, muscle bellies would follow their transposed insertions, whereas under a *pulley model*, muscle bellies would remain near their pre-operative positions. Magnetic resonance imaging before and after transposition clearly supported the pulley model: the paths of rectus muscle bellies remained almost fixed in the orbit despite large surgical transpositions of their insertions.



Because there was some movement of the muscle belly, we termed the new constraints *soft pulleys*.

5. **Histochemistry:** What was holding the muscle bellies back? We conducted a series of studies to anatomically locate and histologically characterize the pulley tissues (Demer, Miller, Poukens, Vinters & Glasgow, 1995).

   Fresh cadaver orbits were exenterated and selectively step and serial sectioned for histochemical and immunohistochemical staining. Dense connective tissue structures within posterior Tenon's fascia near the equator of the globe adjacent to the recti EOMs were found to be sleeves consisting of dense bands of collagen and elastin, suspended from the orbit and adjacent EOM sleeves by bands of similar composition. A monoclonal antibody to human smooth muscle α-actin demonstrated substantial smooth muscle in the pulley suspensions and in posterior Tenon's fascia. Mid-orbital and posterior coronal sections can be schematized as follows:



In the *Tutorial* section of this manual we will compare simulations of muscle transposition surgery, with and without soft rectus muscle pulleys. It will be clear that pulleys are significant determinants of extraocular mechanics.

Again?

The notion of rectus muscle pulleys has arisen before, apparently without the evidence needed to get a fair hearing. As recounted by Scobee (1952), Lockwood (1886) described a band of fibers imbedded in Tenon's capsule crossing the posterior edge of each opening and called these bands the *intracapsular ligaments*. He went on to describe several intracapsular and suspensory ligaments later visualized by Koornneef (1983). Ferrall proposed these structures acted as pulleys, but Whitnall (1932) flatly stated that "there are no pulley bars or intracapsular ligaments, and no need for them" (so there!).

What is a Simulation?

An Orbit document -- a set of fixations, eye parameters, clinical measurements, etc -- is also referred to as a *simulation*.

We provide several simulation examples in the folders

,

and

. We will refer to them in the *Tutorial* section (page 47).

Existing simulations can be opened in all the usual ways: From within Orbit, use **» File » Open** ; from the Finder desktop, double-click on a simulation icon, or drag-and-drop a simulation icon on the Orbit application icon.

To begin a new simulation from within Orbit, select **» File » New**.

When a simulation is open, it is listed in the **» Simulations** menu.

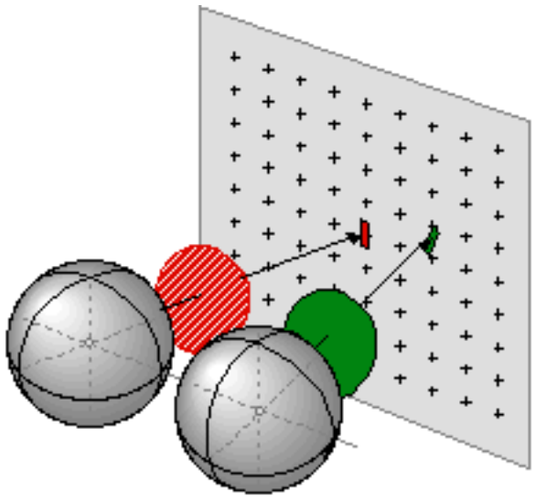
A simulation is open if and only if one or more *simulation windows* -- windows referring to a particular simulation -- are open. Thus, some simulation window always opens with a simulation (see **» Both Eyes » Preferences**), and the simulation is closed when its last window is closed.

Certain windows do not refer to any particular simulation, and so are not simulation windows: These are Preferences, Point of View, Converter, and all of the Help windows.

You can have as many simulations open as memory (the machine's and yours!) permits.

Test of Binocular Alignment

Orbit simulates the common clinical alignment tests in which the two eyes are dissociated (prevented from seeing the same targets), and the patient fixates with one eye as the other follows passively. In Orbit 1.8 either or both eyes may be abnormal.



The figure is a schematic of the Lancaster Test in which the eyes are dissociated by viewing colored targets through colored filters. The patient has been asked to fix the red bar at (0,0), seen only by her left *fixing* eye, and to move the green bar, seen only by her right *following* eye, so that it appears to lie on top of the red bar. Assuming normal retinal correspondence, the positions of the two bars give the gaze angles of the two eyes. If binocular alignment were normal, our patient would have superimposed the two bars. In the case shown, her right eye is 20° exo-deviated (misaligned outward), 5° hyper-deviated (upward), and somewhat excyclo-deviated (twisted top-outwards, around the visual axis).

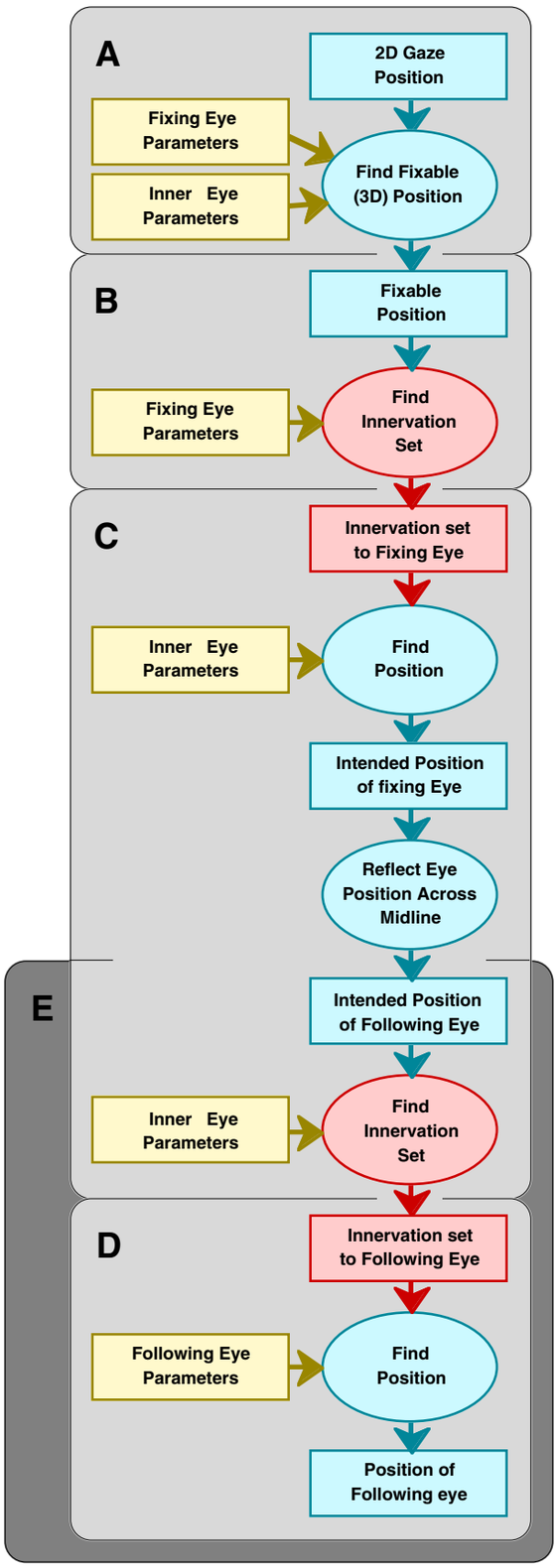
Orbit's simulation, schematized below, follows the clinical test, beginning with the fixing eye.

First (Figure part **A**), the operator *Find Fixable Position* calculates the torsion that the (possibly abnormal) fixing eye would assume at a chosen 2-dimensional gaze angle. Then, (**B**) with all 3 gaze coordinates, we can find the innervations that would bring the fixing eye to that position.

To implement Hering's Law (**C**), we use *Inner Eye Parameters* to transform the *Innervation Set to Fixing Eye* into "position space", reflect the position across the midline, and transform back into "innervation space". The Inner Eye is simply a third set of eye parameters that is usually left with the normal values supplied, but may be modified (**» Both Eyes » Inner Eye Parameter Editor**).

Finally, (**D**) this *Innervation Set to Following Eye*, and a description of the following eye go to *Find Position*, which calculates the position of the following eye.

Orbit™ 1.8 Binocular Model



Find torsion for arbitrary fixing eye (new in Orbit 1.8).

Now we can find the 3 reciprocally-related innervation pairs that would drive the Fixing Eye to the Fixable Position.

But the 2 eyes are mirror images (eg, when the fixing eye abducts, the following eye adducts), so to get Following Eye Innervations, we must "reflect" the Fixing Eye Innervations across the midline.

Now it's a simple matter to find the position of the Following Eye.

If the fixing eye is normal, only the calculations in box **E** are necessary (this was the total calculation in Orbit 1.0).

We can compare such a set of simulated gaze positions with a set of clinical measurements, altering eye parameters to optimize the fit.

The outcome of such a simulation is a diagnosis of the patient's disorder in biomechanical terms. Similarly, we can find the orbital manipulations that would cause our model sick eye to assume normal, conjugate gaze positions. The outcome of this simulation would be a treatment plan. Many aspects of the model eye can be manipulated in pursuit of a diagnosis or treatment. The Parameter Fitter, described below, partially automates the trial-and-error process.

Eye Position

Coordinates for Translation

The eye is cushioned in the orbit by elastic fat pads, so it cannot only *rotate*, it can also *translate* slightly. For most purposes we can ignore globe translation, but in some restrictive and co-contractive syndromes, globe translation is a significant factor, as we will see when we analyze Duane's syndrome. For now, we just note that *specifying* translation is straightforward, since we are all familiar with the conventional *Cartesian coordinate system* for describing translational motion. Orbit uses Cartesian coordinates fixed to the skull, with origin at the point where the center of the globe falls when the eye muscles exert no forces. The three axes are oriented with a protrude-retract axis aligned with the orbital axis, an upward-downward axis perpendicular to the first and as close to vertical as possible, and a sideward-middleward axis perpendicular to the other two. The names used in Orbit to refer to these axes are the names of the positive directions:

sideward Positive sideward movement is translation toward the side of the head. Sideward movement is not the same as conventionally defined "lateral" or "temporal" movement, because our

coordinate system is turned outward to align with the orbital axis.

protrude Positive protrusion means the eye bulges out of the orbit. Negative protrusion, or retraction, is more frequently spoken of in strabismus.

upward The upward-downward axis is tilted slightly from the common anatomic superior-inferior axis, because our coordinate system is pitched slightly backwards to align with the orbital axis.

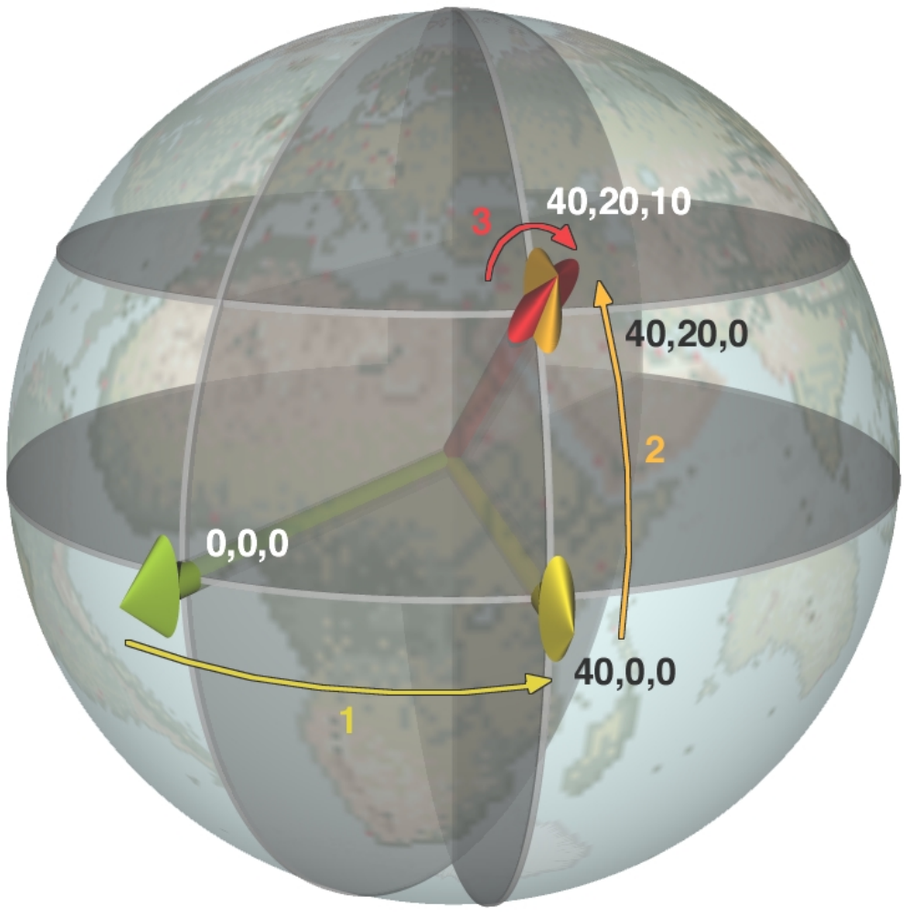
Only protrusion-retraction is of practical interest in strabismus.

Rotation is more of a problem than translation, and it is a deep problem: rotations are mathematically more complex than translations, and further, these complexities are of an unfamiliar kind. Below, we discuss how eye rotation is described in Orbit.

Coordinates for Rotation

Any given 3-dimensional rotation can be described with 3 numbers, or coordinates, by definition. There are many correct rotational coordinate systems, and to describe the rotation of an object like an eyeball, one must first choose a system, on the basis of its usefulness, familiarity, aesthetics, or something else. It is important to understand that the same 3-D rotational position may have different coordinate values when described in different coordinate systems.

Two popular coordinate systems for eyes are *Fick coordinates* and *Helmholtz coordinates*. The 3 Fick coordinates are named *longitude, latitude and torsion*; the 3 Helmholtz coordinates are named *elevation, azimuth and torsion.* Although the same term is used to describe the third coordinate in both systems, Fick and Helmholtz torsion are only qualitatively similar: they both describe rotation about a visual axis, the direction of which is determined by the first two coordinates. But because the first two coordinates are different (except in some special cases), torsion values describing the same rotation are different, as well.



Orbit uses Fick rotational coordinates.

You may already be familiar with Fick coordinates as the longitude and latitude lines conventionally drawn on a globe of the earth. Imagine the eye at the center of the globe, and its visual axis pointing at the intersection of 0° longitude and 0° latitude (green arrow). First, rotate the eye so that the visual axis moves along the equator, until it points to, say, 40° longitude (yellow arrow). Second, rotate the eye so that the visual axis moves straight up the 40° longitude line, until it points to the 20° latitude line (orange arrow). The longitude-latitude coordinates of the eye are, by definition, now {40°, 20°}. Notice that the elongated dimension of the arrow, which was parallel to the local longitude line at {0°, 0°, 0°} and at {40°, 0°, 0°}, remains parallel at {40°, 20°, 0°}. This means that torsion in the Fick system is zero. Of course, one more independent dimension of rotation remains: without changing longitude or latitude, you can rotate the eye about the visual axis. If you rotated the eye, say, 10° about the visual axis (red arrow, torsion exaggerated), its Fick coordinates would be {40°, 20°, 10°}.

We are also free to rotate the eye using a different coordinate system. Imagine the way an astronomical telescope is mounted: the telescope is attached to an "azimuth" disk by a perpendicular axis that carries a pointer. Rotating the telescope about the axis points to angle markers drawn on the disk. The disk itself is mounted so that it can be tilted up or down about some axis. Such a mechanical arrangement follows the Helmholtz system for describing rotation. First, from some conventional starting position (the position that we call straight-ahead gaze, {0°, 0°, 0°}), we elevate the disk by, say, 40°. Second, we rotate the azimuth pointer from 0° to 20°, and third, we twirl the telescope -- or eye -- about its visual axis by, say, 10°. We are now at Helmholtz coordinates {40°, 20°, 10°}. This is not the same position as Fick {40°, 20°, 10°}! If you doubt this, imagine the rotation {90°, 90°, 0°} in the two systems.

Rotational Positions in Orbit

Before we can specify a rotational eye position we need to choose a coordinate system and an origin, name each coordinate, and decide which direction will be positive. In Orbit, we use the Fick coordinate system, and take *primary position*, straight ahead, as {0°, 0°, 0°}. The reasons are partly historical, in that Robinson (1975) used Fick coordinates, and partly practical, because clinicians speaking about "horizontal" and "vertical" eye movement, are usually, it seems, thinking of a longitude-latitude system. Note that "horizontal" and "vertical" are not well defined unless a coordinate system is specified. In connection with Orbit simulations, "horizontal" rotation will always mean a change in longitude only, and "vertical" rotation will always mean a change in latitude only, according to the Fick coordinate system.

The term *gaze* is conventionally used to refer to the direction of the visual axis only, that is, to horizontal and vertical components, leaving torsion unspecified. Thus, we specify *intended gaze* in Orbit simulations, and fixing eye gaze in clinical eye alignment tests, because patients are not asked to bring the fixing eye to a specified torsional position, and indeed, without special training (Nakayama and Balliet, 1977), they cannot.

Finally, we have chosen coordinate directions that take advantage of the mirror symmetry of the eyes: eg, we use abduction-adduction instead of rightward-leftward. This allows us to describe gaze mechanics in a way that is valid for either eye. We use coordinate names that indicate which direction is positive: *abduction*, *elevation* and *extorsion*:

abduct or abduction, is the 1st Fick coordinate rotation away from primary position. Positive rotation about this vertical axis moves the visual axis away from the body's midline, along the equator.

elevate or elevation, is the 2nd Fick coordinate rotation. It is rotation in the plane of the local longitude (see "globe" figure above). Positive rotation about this horizontal axis moves the visual axis up along a longitude line.

extort or extorsion, is the 3rd Fick coordinate rotation. It is rotation about the visual axis, such that the top of the eye moves laterally.

Deviations

It is useful to speak of a *fixing eye* and a *following eye*. In some alignment tests, the following eye is actually covered (and, so, is referred to as the covered eye), and the patient voluntarily moves the fixing eye to various standard gazes. In other tests, neither eye is covered, but it is arranged that there is nothing visible to both eyes, that is, that there is no fusional target. The position of the following eye is ascertained as the patient fixates standard gaze targets.

Deviations are differences between following eye and fixing eye rotational positions. One might more descriptively (and less humorously) call them "misalignments", but "deviations" is conventional.

exo-dev or exodeviation = (following eye abduction) + (fixing eye abduction).

The "+" appears because of the mirror symmetry of the eyes. Exodeviation is positive when the following eye is more abducted than fixing eye is adducted

hyper-dev or hyperdeviation = (following eye elevation) - (fixing eye elevation).

Hyperdeviation is positive when the following eye is more elevated than fixing eye.

excyclo-dev or excyclodeviation = (following eye extorsion) + (fixing eye extorsion).

The "+" appears because of the mirror symmetry of the eyes. Excyclodeviation is positive when the following eye is more excyclorotated than the fixing eye is incyclorotated.

Torsion, Of Course, Depends on the Coordinate System

Torsion, as we have explained, is the third coordinate of 3-D rotation.

What is "normal" or "physiologic" torsion? We have seen that 3 independent component rotations -- or 3 "degrees of freedom" -- are available for 3-D rotations. *Donder's Law* states that the eye position control system uses only two degrees of freedom: torsion is not independently controlled, and for each gaze, the normal eye always assumes some particular torsion. *Listing's Law* tells what that unique torsion value is, that is, Listing's Law gives a torsion value for each pair of numbers specifying gaze. We should not now be surprised that the value of this *normal* or *Listing torsion* depends on the coordinate system we use. Because of the way a normal eye (or at least, one that obeys Listing's Law) rotates, it turns out that in both Fick and Helmholtz coordinates, torsion is zero for pure elevation-depression, and for pure abduction-adduction ("secondary gaze"), but non-zero elsewhere ("tertiary gaze). Further, when torsion is non-zero, it is different in the two systems.

Interestingly, it turns out to be possible to define yet another coordinate system, in which torsion for an eye that follows Listing's Law is zero everywhere. We find these *Listing coordinates* useful when discussing how extraocular connective tissue contributes to enforcing Listing's Law (see below), but not for much else. Coordinated innervations, incidentally, provide the other contribution, so if something is wrong with

extraocular tissues or with the brainstem, non-Listing torsions can result.

Excyclo, short for *excyclorotation,* and the directionally uncertain *cyclorotation,* are conventional terms for the amount of torsion in excess of Listing torsion, that is, for abnormal torsion. Cyclorotation describes single eyes, and is zero at all gaze angles for normal eyes, by definition.

Extorsion? Excyclo?? Excyclo-Dev?!?!

(If you've made it this far, you might as well push on to the end of the section!)

There are three different notions in common use that involve rotation of the eye about its visual axis. Often, the concepts are not distinguished, or one term is used indiscriminately. We distinguish the following terms:

Extorsion, as we have explained, is simply the third coordinate of 3-D rotation, with a hint about the positive direction.

Excyclo-Dev, or *excyclodeviation,* intrinsically involves two eyes. Certain clinical tests of binocular eye alignment, such as the Lancaster test, yield a value that is the difference between torsions in the fixing and following eyes. That is, with normal retinal correspondence, the patient may place his red streak at an angle to the examiner's green streak, either because his following eye has abnormal torsion (the usual, possibly mistaken, presumption), his fixing eye has abnormal torsion, or both. Such alignment tests measure the <u>difference</u> between fixing and following eye torsions. There is no conventional term to specify this difference, so by analogy with "exodeviation" and "hyperdeviation", which refer to horizontal and vertical misalignment of the following eye relative to the fixing eye, we coin the terms *cyclodeviation* and *excyclodeviation,* and the abbreviation *excyclo-dev,* to refer to torsional misalignment of the following eye relative to the fixing eye.

To summarize:

> Torsion (*extort*) is rotation about the visual axis.
>
> Listing Torsion *(listing)* is normal torsion according to Listing's law.

Cyclorotation: *excyclo = extort - listing.*

Cyclodeviation: *excyclo-dev = following eye extort + fixing eye extort*, where the "+" occurs because of reflection across the midline).

The **Mechanical State Viewer** shows all of the values mentioned for a given intended gaze. You may find it helpful to review the above discussion while looking at the Deviations and Eye Rotation values for a tertiary gaze (eg, 30,20).

Limitations of Orbit

In Orbit 1.0 the fixing eye had to be normal. Orbit 1.5 and 1.7 did not require that the fixing eye be normal, only that it obeys Listing's Law, that is, has normal torsion[†]. The following eye could be arbitrarily abnormal.

With Orbit 1.8, this last restriction is lifted: the fixing eye, too, may be arbitrarily abnormal.

The method used by Orbit 1.8, outlined in part "A" of the Orbit 1.8 Binocular Model flowchart, above, is similar to that described by Miller and Robinson (1984).

[†] The reason for the Listing's Law restriction in earlier versions can be explained with reference to part "B" of the Lancaster Test simulation flowchart. In part B we calculate innervations to the fixing eye. *Find Innervation Sets* needs to be given all three coordinates (horizontal, vertical and torsional) of each *Fixing Eye Position* and all *Fixing Eye Parameters* to do its work. Generally, we specify only horizontal and vertical components of the fixing eye position (as with the Intended Gaze Selector, discussed below), and make some assumption about torsion: Our assumption in Orbit 1.7 and earlier versions was that torsion of the fixing eye was determined by Listing's Law.

If the fixing eye had significant abnormal torsion, then Orbit's assumption of Listing torsion would produce errors in simulated following eye positions. For instance, if the fixing eye were actually extorted (eg: SO palsy), Orbit would still suppose, eg, that the medial rectus muscle (MR) of the fixing eye had only horizontal action in primary position, and innervate the following eye on that assumption. Actually, the MR of the extorted fixing eye had developed some elevating action, requiring general alteration of innervations to the fixing eye, and so by Hering's Law, to the following eye. Thus, the simulation of following eye positions would have been in error.

PowerMac™ computers perform these computations quickly. If you are using a Non-PowerMac, you will need to be very patient, and pay close attention to the issues discussed in the section of this Manual on Speed 115). We do not recommend you use Orbit on a Non-PowerMac, except for evaluation.

Tutorial Examples

As with any tool, Orbit's utility depends on your skill. To show you how to work with Orbit, we will develop several simulations. These simulations are saved in the LSO Palsy Example, RLR Palsy Example and Duane Syndrome Examples folders, for your examination.

We will point out the steps you should actually perform on your Mac, if you wish to follow the presentation.

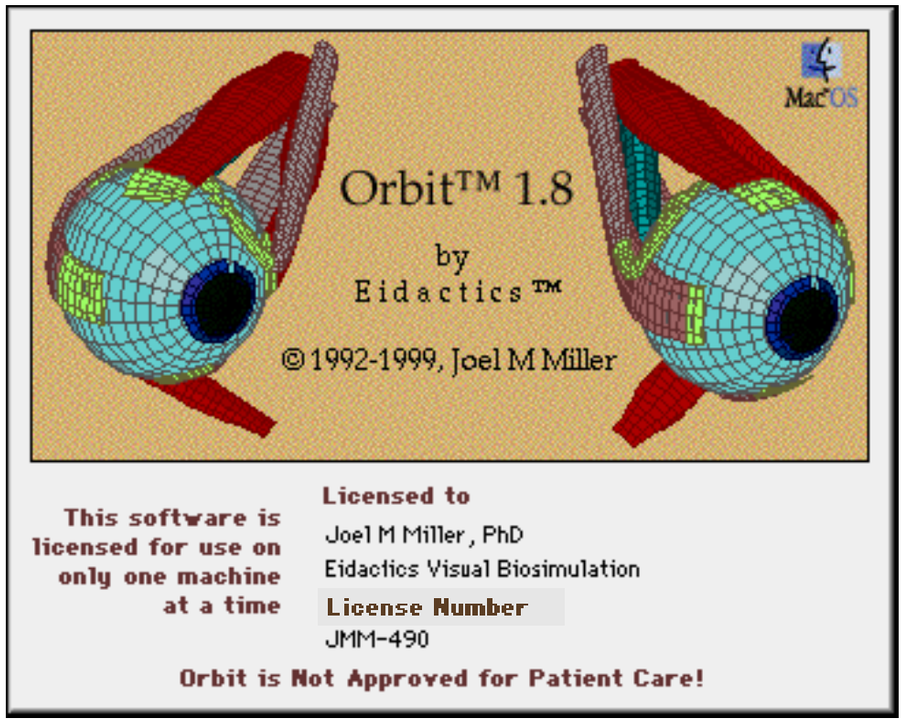
Superior Oblique Palsy

First, we will simulate a composite case of SO palsy, in the course of which we will use many basic Orbit functions. We will also see some of the strengths and limitations of Orbit, and some of the limitations of current methods of measuring binocular alignment. We will also confront some gaps in our current understanding of some muscle actions (topics for future research). Recall that, where Orbit cannot confidently perform a calculation, it does nothing. By leaving such matters to the User, Orbit allows hypotheses to be tested.

Launch Orbit

☞ Launch Orbit by double-clicking on the

icon. The Orbit *splash screen* appears:



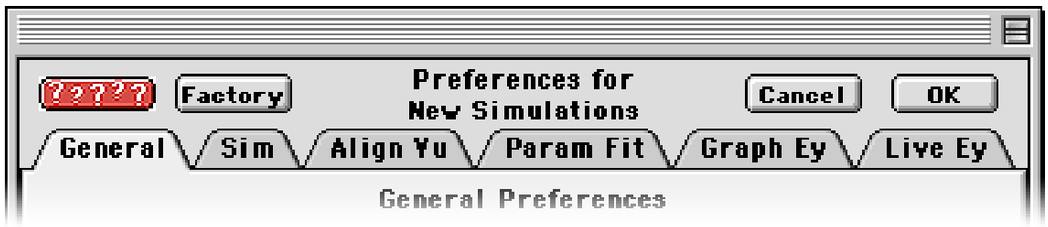
Here you see:

- The Orbit version. Is this the version you intended to run?
- Registration -- the person identified is responsible for all use made of this licensed software.

View the Alignment Pattern

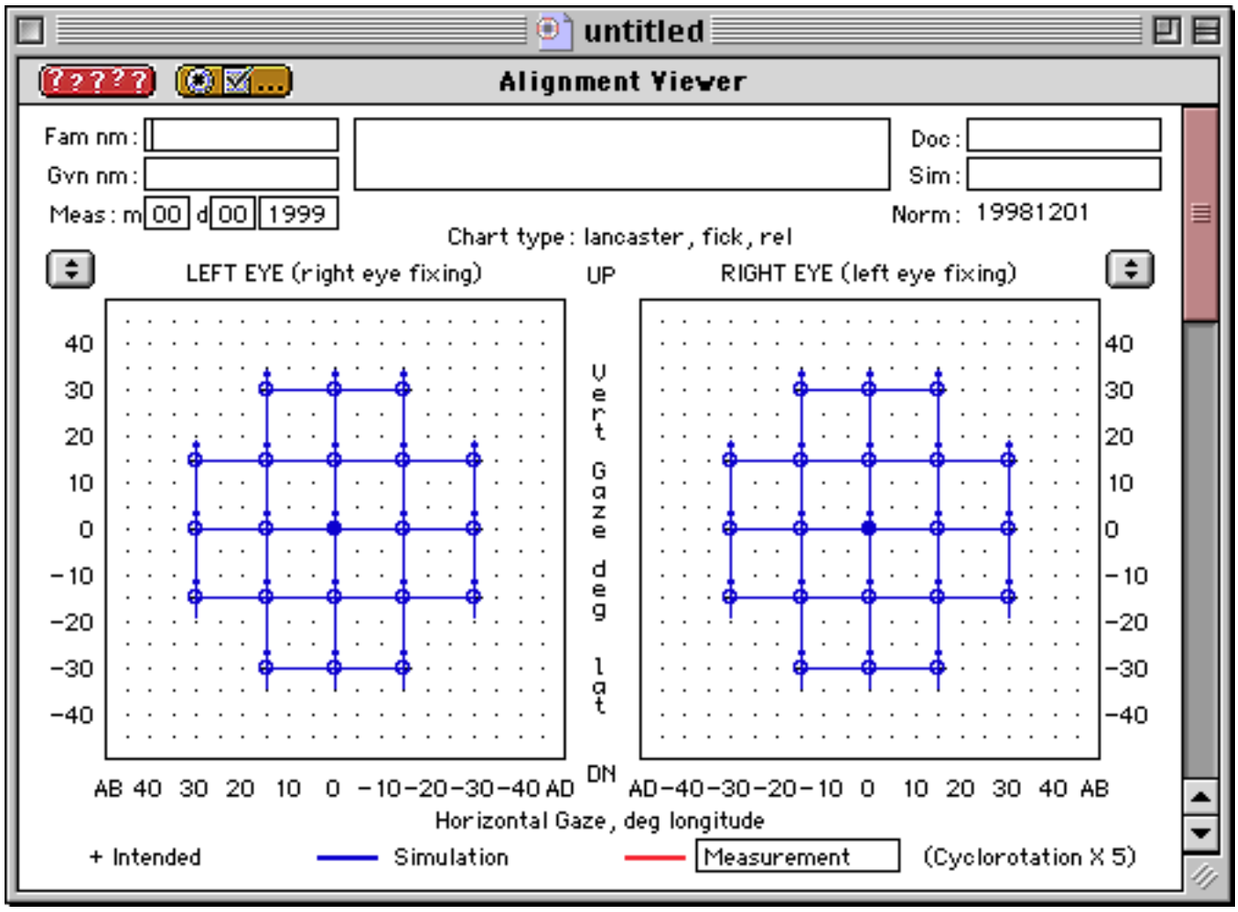
If your copy of Orbit is factory-fresh, all of its Preferences are set to standard, "factory" values. A new simulation will open with the help window **What Is Orbit?**, and the **Alignment Viewer**. Read this help window, if you have not already done so.

☞ Otherwise, to be sure you can follow the examples below, close any open windows, select **» Both Eyes » Preferences for New Simulations...**, click Factory, and then OK:



☞ Then, create a new simulation with **» File » New.**

The **Alignment Viewer** will open. It should look like this:



On this Hess-Lancaster-type chart, each *intended gaze position* is represented as a small black cross, "**+**", in the

intended position of the following eye, that is, the position that would be assumed by a normal following eye. Positions of the following eye are shown as blue circles, "o", with connecting lines to emphasize the pattern. An arrow through each circle shows cyclorotation (torsion in excess of normal Listing's Law torsion), as tilt from straight up, multiplied by 5 for visibility. The simulated eyes are normal, because we haven't modified them yet. Therefore, the blue circles lie exactly on top of the black crosses, obscuring them until we introduce an abnormality.

☞ Examine the **Alignment Viewer** by turning on Balloon Help (**» Help » Show Balloons**). Point to the various buttons and fields to discover what they are for. When you are done, **» Help » Hide Balloons**. Click the Window Help Button ????, and read the description of the window. There is a more complete discussion of the **Alignment Viewer** in the Reference section of this manual.

☞ Enter some identification:

Intended Gaze

Why do we use *intended* gaze positions? The conventional alternative would be to specify positions of the *fixing eye* for comparison with the positions of the *following eye*. But then, because of the mirror symmetry of the eyes, calculating *deviations* requires interchanging abduction and adduction and reversing the sign of torsion for the fixing eye. When you represent deviations graphically, as in a Hess-Lancaster chart, you are using the notion of intended gaze implicitly, as we have discussed.

Import Alignment Measurements

Inside the Orbit™ 1.8 f folder, you will find the

LSO Palsy Example folder. In this folder we have provided alignment measurements that are the mean of measurements we collected from 3 cases of left superior oblique palsy, confirmed by MRI (Demer, et al, 1995)

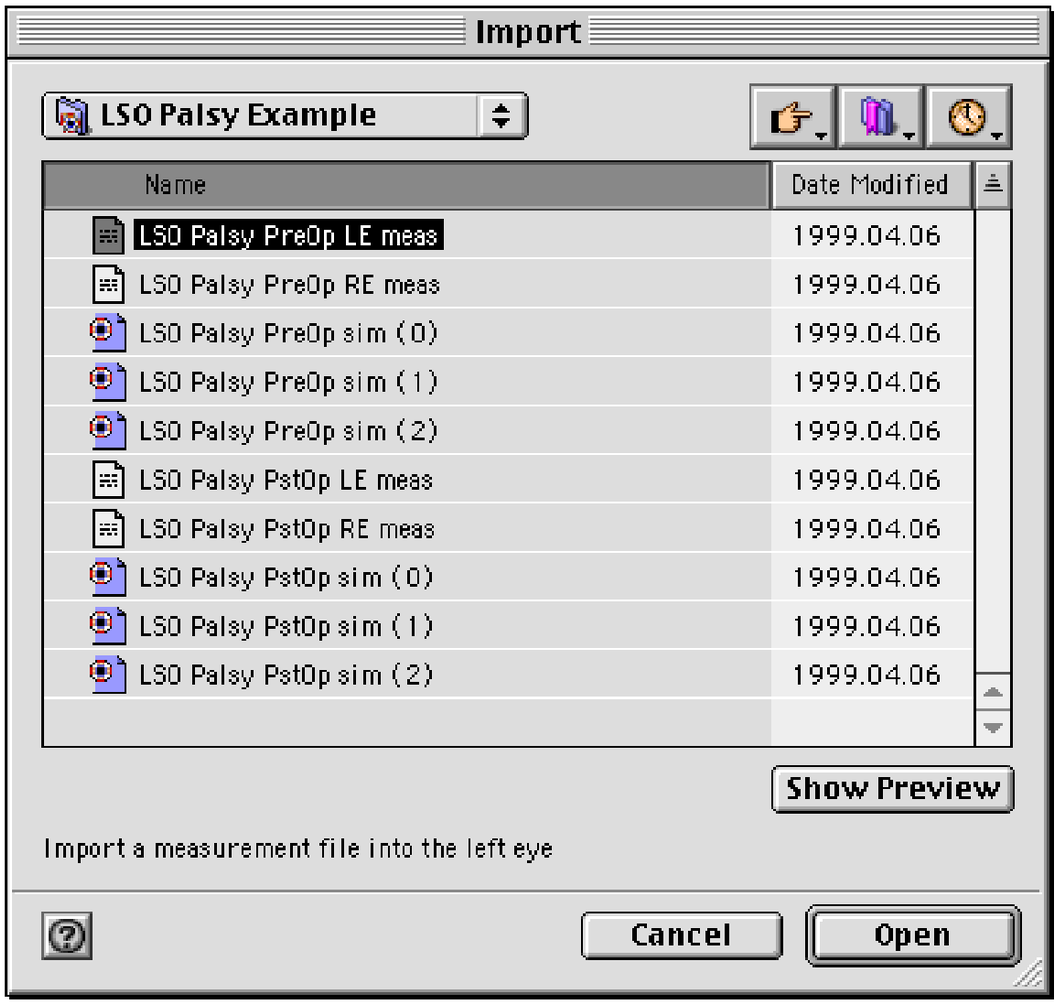
and with similar surgical treatment: LSO Palsy PreOp LE meas

and LSO Palsy PreOp RE meas.

We will refer to such data as *clinical alignment measurements, alignment measurements,* or just *measurements,* the important distinction being between *measurements* and *simulations*. Simulations can predict measurements, and measurements can test simulations, but they are not the same.

Orbit measurement files are plain text files, like those that can be produced by text processor and spreadsheet programs (these programs must usually be set to output plain text). Orbit can also save measurements (and simulated positions) as text files. Details are given in the Orbit Reference section, below.

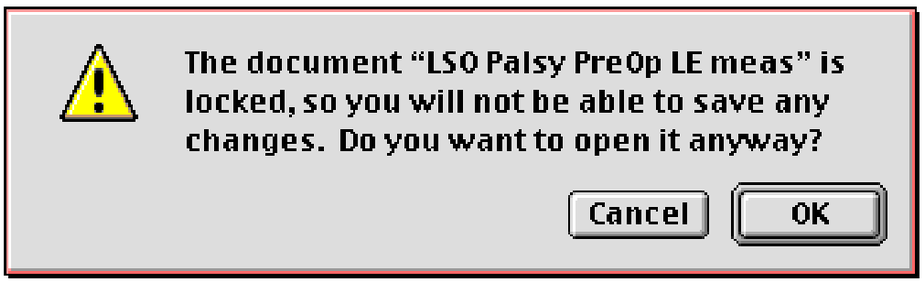
☞ To import pre-operative measurements into Orbit's left eye, select » **Left Eye** » **Import Measurements...**, which will lead to a standard Macintosh File Dialog (we show the new file dialogs, supported by Apple Navigation Services, incorporated in MacOS 8.5; if you are using an older operating system, you may see the older style file dialogs instead). Navigate to the LSO Palsy Example folder:


Import
LSO Palsy Example
Name
Date Modified
LSO Palsy PreOp LE meas 1999.04.06
LSO Palsy PreOp RE meas 1999.04.06
LSO Palsy PreOp sim (0) 1999.04.06
LSO Palsy PreOp sim (1) 1999.04.06
LSO Palsy PreOp sim (2) 1999.04.06
LSO Palsy PstOp LE meas 1999.04.06
LSO Palsy PstOp RE meas 1999.04.06
LSO Palsy PstOp sim (0) 1999.04.06
LSO Palsy PstOp sim (1) 1999.04.06
LSO Palsy PstOp sim (2) 1999.04.06
Show Preview
Import a measurement file into the left eye
Cancel
Open

☞ Locate and Open the **LSO Palsy PreOp LE meas** file.

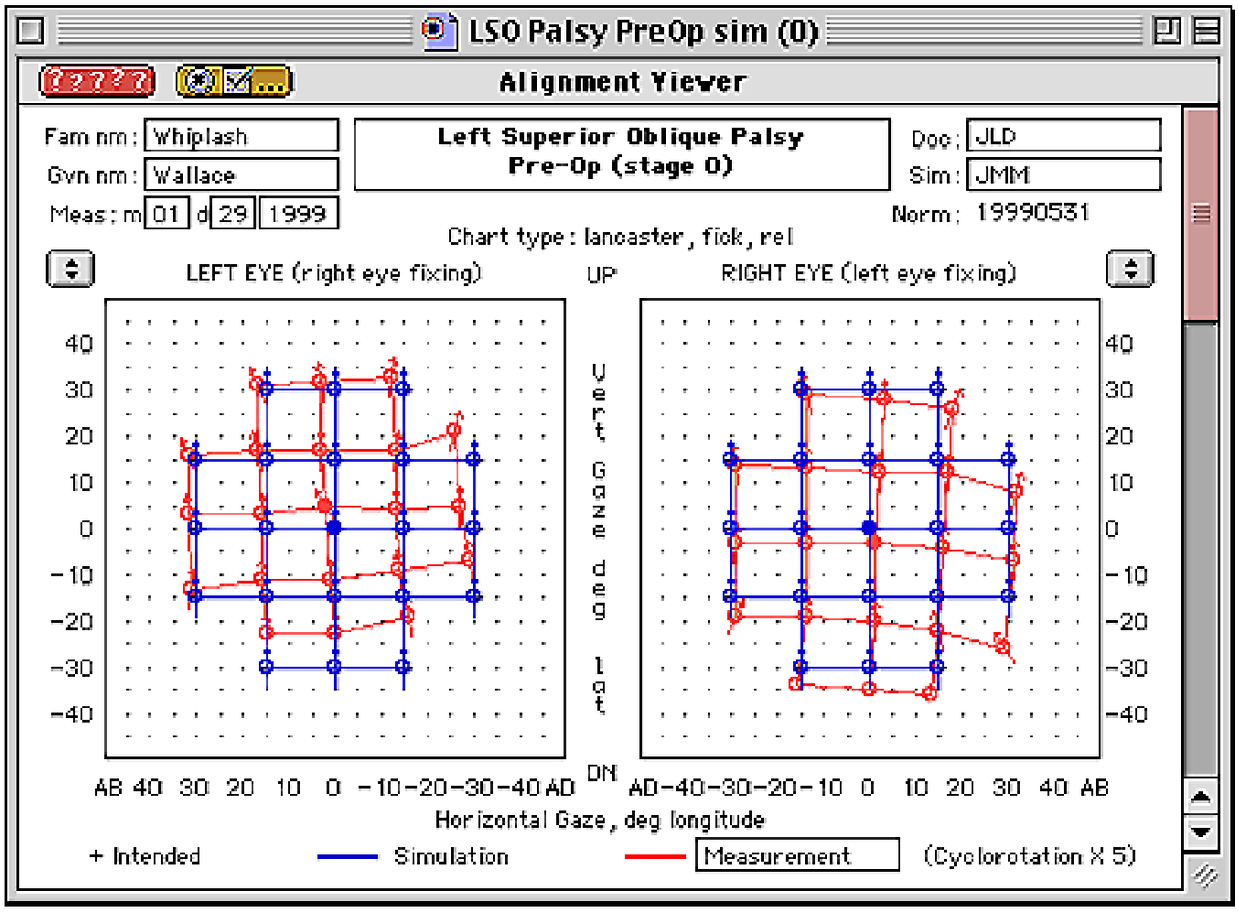
Similarly, select » **Right Eye** » **Import Measurements...** to import **LSO Palsy PreOp RE meas** into Orbit's right eye.

We have locked the measurements files to prevent inadvertent changes, so you will see an alert when you open them:


The document "LSO Palsy PreOp LE meas" is locked, so you will not be able to save any changes. Do you want to open it anyway?
Cancel
OK

Just click OK and continue. (We have saved this stage of the simulation as LSO Palsy PreOp sim (0)).

☞ Bring the Alignment Viewer into the foreground by clicking or selecting it from the menu bar:

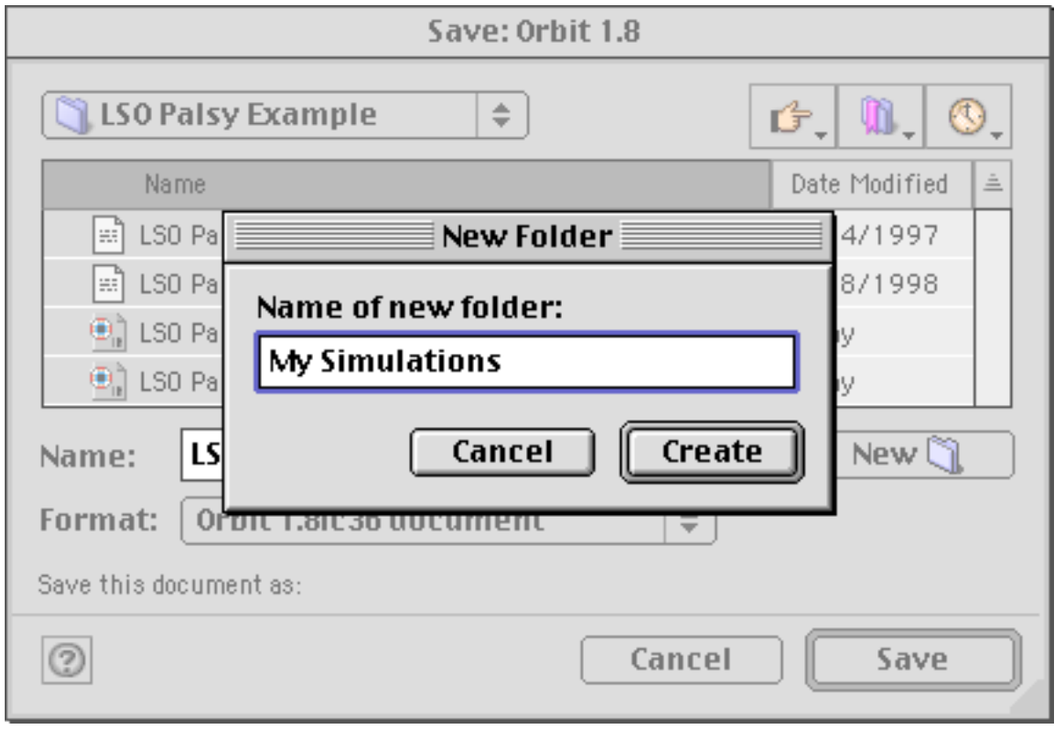


The imported alignment measurements are shown in red (gray in an achromatic image).

Alignment measurements plotted along with simulations help evaluate a simulation as it is developed by trial-and-error. It is also possible to work on simulations without entering measurements, or use the alignment chart to display clinical measurements alone.

☞ If you wish, you can print the Alignment Viewer with **» File » Print**.

☞ You may want to save your own copy of the simulation as it now stands with **» File » Save**. We have locked the measurement and simulation files we provided, so don't worry about inadvertently overwriting them. Create a new folder for your simulations:



☞ If you are working with Orbit demo (which disallows saving), simply **» File » Quit** now, if you want a break. To resume later without starting over, open

LSO Palsy PreOp sim (0).

Simulate an Abnormality with Live Eyes

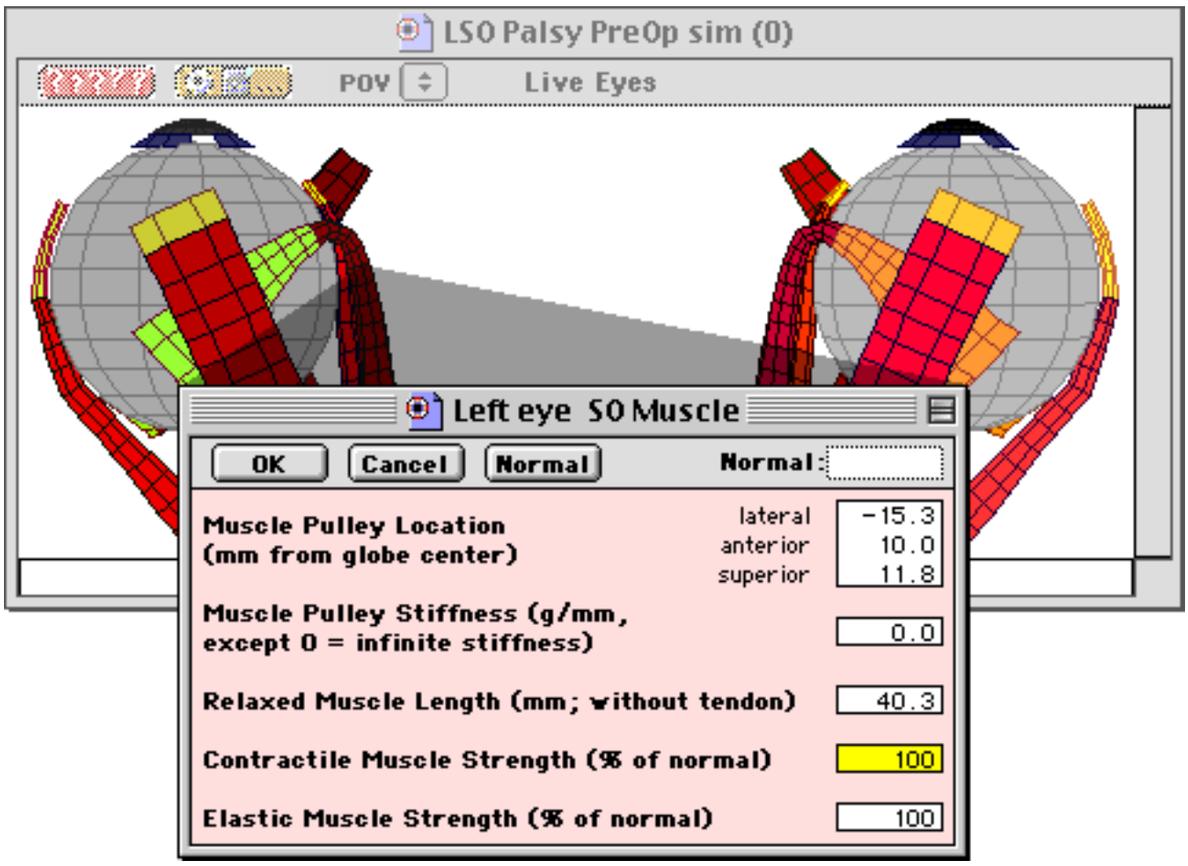
One way to create an abnormality is with the **Live Eyes** window.

The imported measurements (and, in the present case, MRI findings) suggest left superior oblique palsy. That's where we'll begin.

☞ Select **» Both Eyes » Live Eyes.** The Live Eyes window will appear. You may need to use the scroll bars and size box to center the picture.

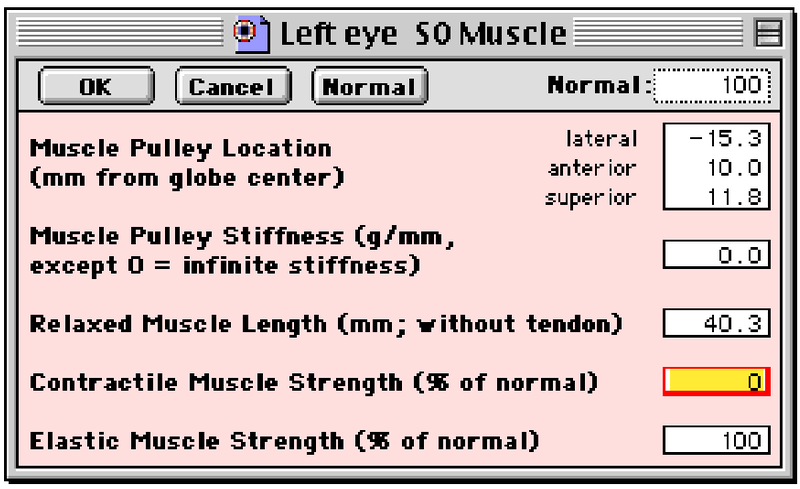
☞ If the Live Eyes do not look like the figure below, click POV and choose the Superior point of view.The Live Eyes have 26 regions that produce pop-up windows when you click on them: the 12 tendons, the 12 muscles, and the 2 globes.

☞ Click once on the left superior oblique muscle:



The muscle Pop-up window allows muscle parameters to be modified. In a simple SO palsy, contractile muscle force is 0.

☞ To simulate simple SO palsy, highlight the Contractile Muscle Strength box, change it from 100% to 0, and click OK:



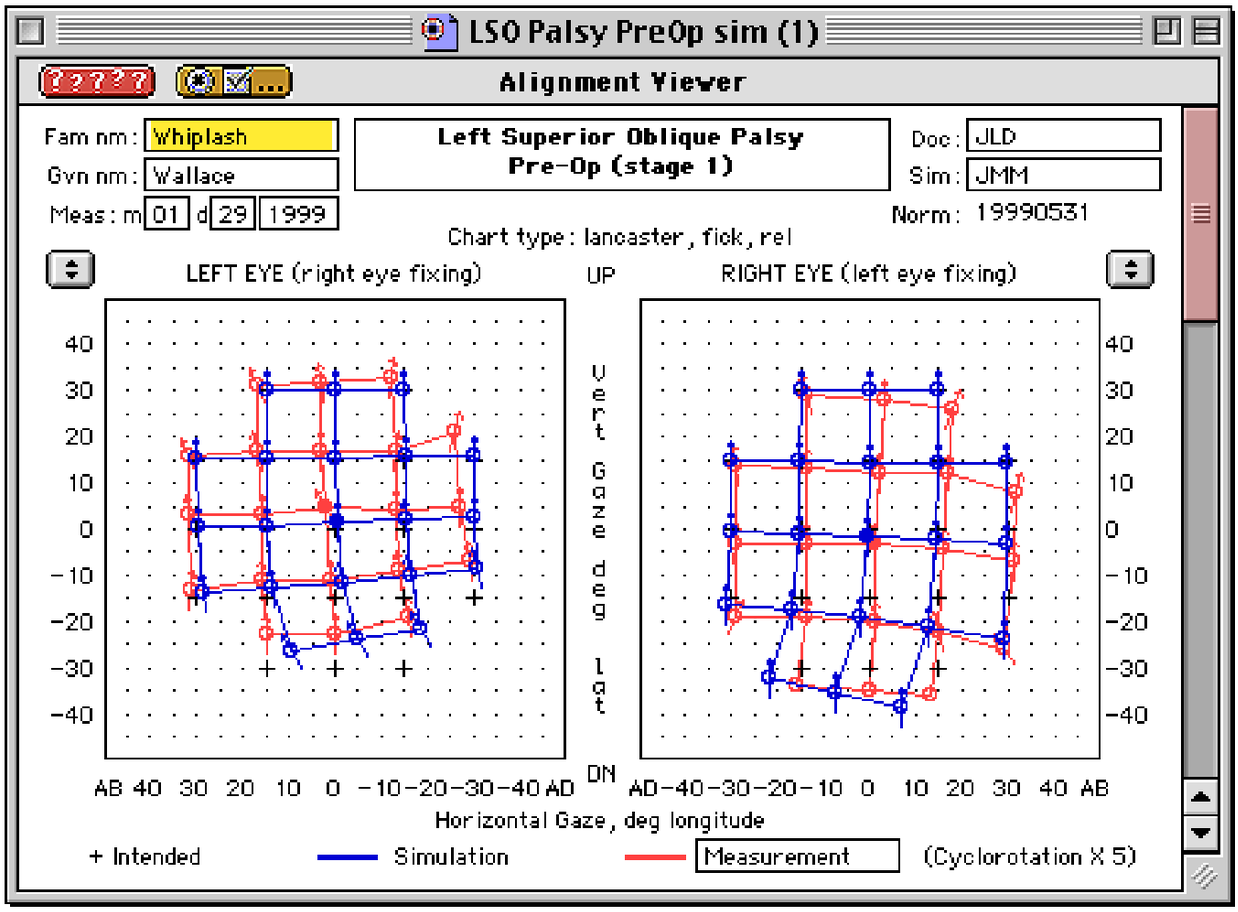
If the title bar of the Live Eyes window was visible in the background, you may have noticed that inverted and upright question marks (¿ ... ?) appeared around the simulation name when you altered Contractile Muscle Strength in the pop-up window. Similarly, the Alignment Viewer shows the question marks now:

☞ Click on the Alignment Viewer or select

» Both Eyes » Alignment Viewer.

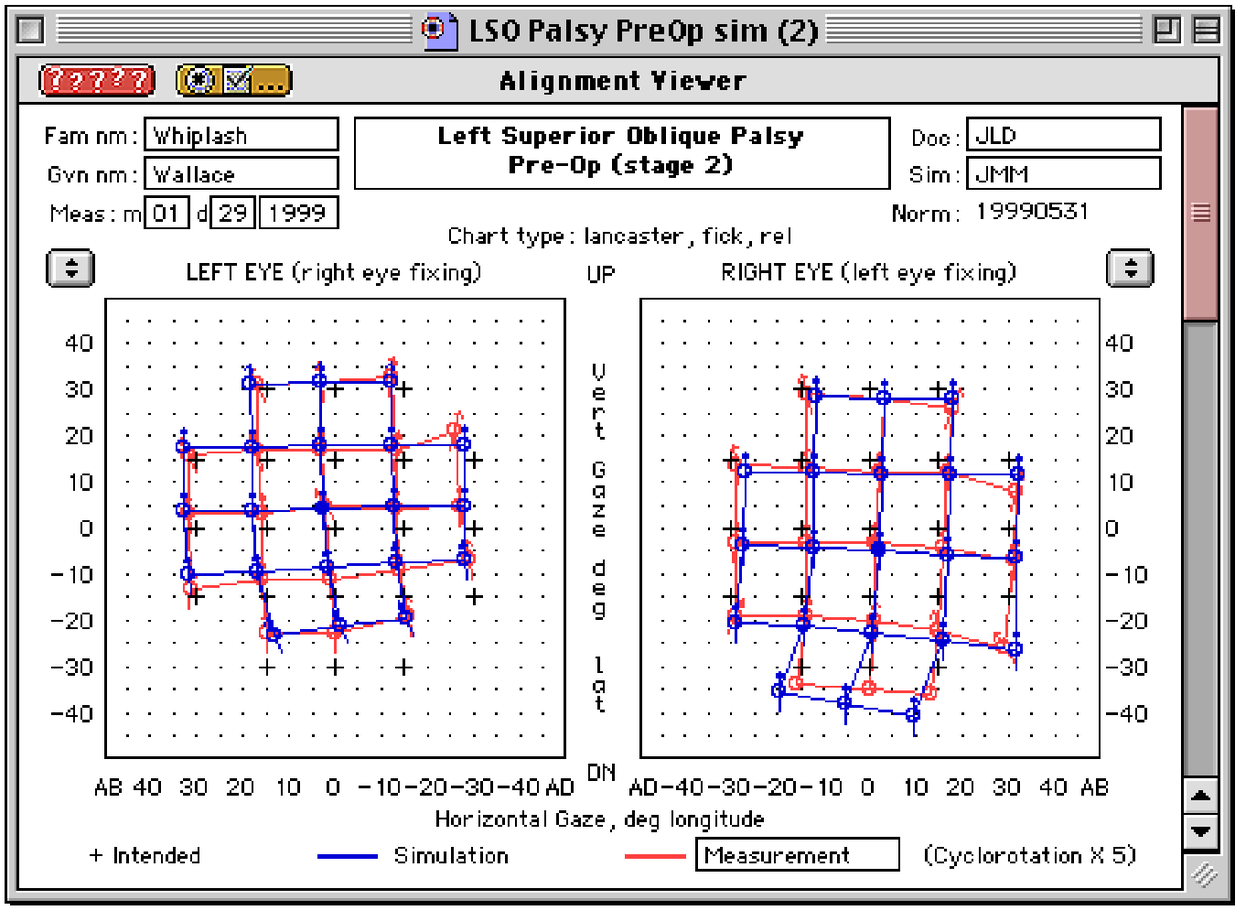
Notice that the question marks disappear when the Alignment Viewer comes into the foreground. The question marks indicate that the window is not up to date. For efficiency, we only update windows when they are brought into the foreground, eg, by clicking them. Windows in the background (which are always dim) may therefore not reflect changes you have recently made, and the question marks appear to remind you of this.

We have saved this stage of the simulation as LSO Palsy PreOp sim (1):



With just one parameter change, the simulation is already fairly good. The simulated left eye matches the measurements in showing limited depression, especially in adduction, and a V-pattern. The tilt of the arrows, which indicates torsion, shows that simulated cyclorotation depends on vertical gaze, whereas measured cyclorotation is less orderly. It is not unusual to find that measurements of cyclorotation do not match simulations: this may be because clinical measurements are often unreliable (Miller and Demer, 1999). In any case, note that the tilt of cyclorotation arrows in the Alignment Viewer is multiplied by 5 for visibility, so that most of these discrepancies are small. Expected secondary deviations are seen in the simulated following right eye, and these also match the clinical data.

The remaining systematic differences are that the simulation shows greater eso- and left hypophorias, compared to the measurements. Regarding the left hypophoria, we suppose that, as a consequence of the chronically elevated posture of the left eye, the LSR has shortened by 2 mm (from 32.4 to 30.4). The small residual horizontal difference between simulation and measurement is nulled by shortening LLR by 0.7 mm (from 36.2 to 35.5) and lengthening LMR by 0.7 mm (from 31.0 to 31.7). We have saved this simulation as LSO Palsy PreOp sim (2):

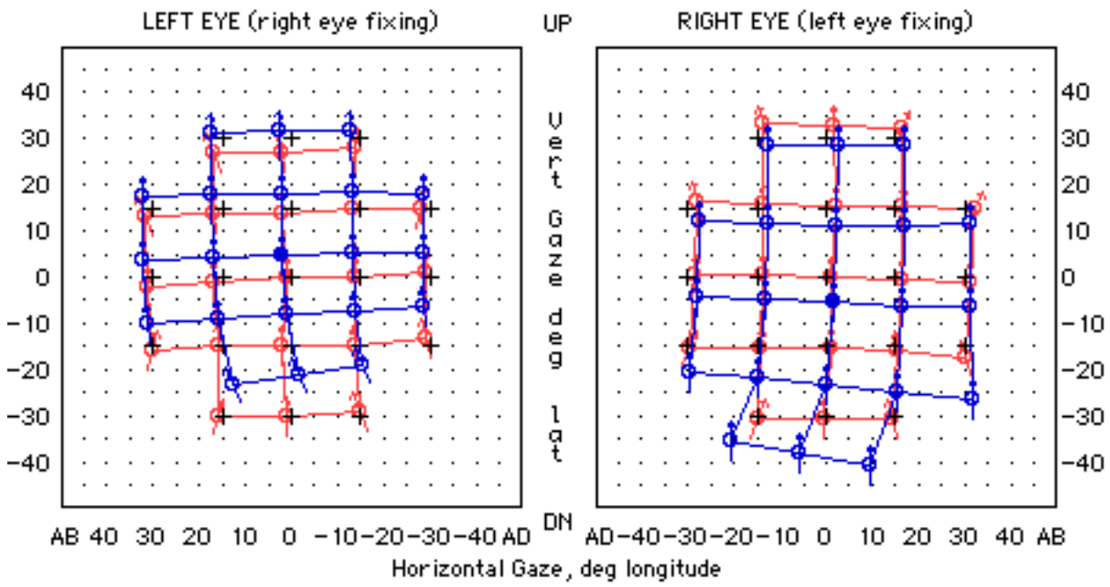


In other cases of SO palsy, we might need to consider additional changes secondary to the palsy, such as: (1) atrophy of the denervated LSO, that is, subnormal *elastic force*, in addition to its absent contractile force, and (2) adaptation of the cyclovertical muscles which, chronically held at abnormal lengths, have adapted by adding or subtracting serial sarcomeres (Tabary, et al, 1972; Williams & Goldspink, 1973), so that their resting lengths are abnormal.

Plan a Treatment

Now that we have a simulation of the disorder, we can experiment with treatments.

☞ Open LSO Palsy PreOp sim (2), and import the post-operative measurements LSO Palsy PstOp LE meas and LSO Palsy PstOp RE meas. You will by warned about overwriting the existing pre-operative measurements, which you want to do. Save the result as (» **File** » **Save As...**) LSO Palsy PstOp sim (0):

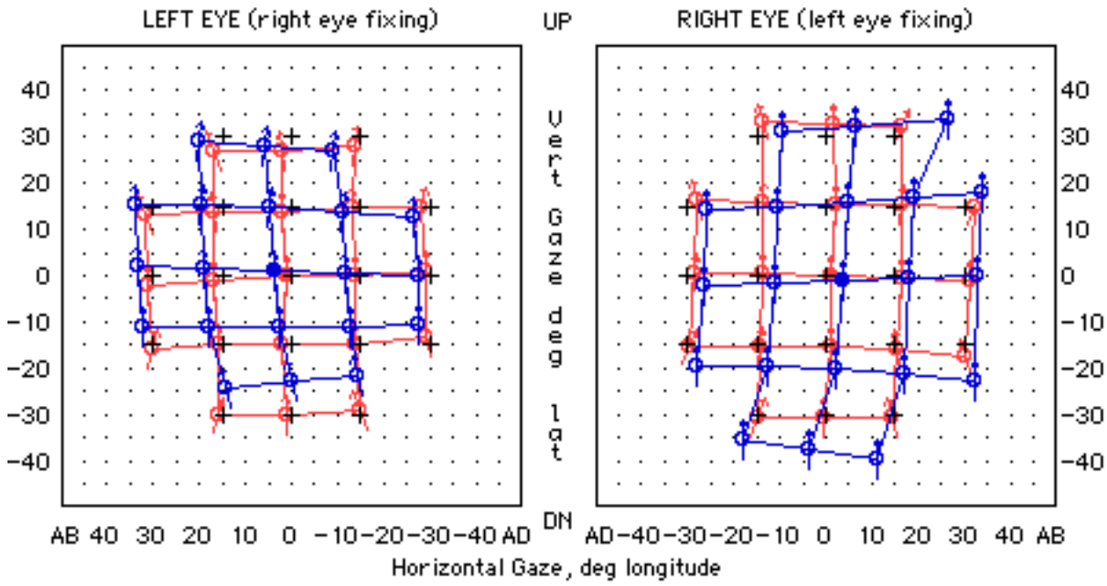


Our aim is now to match the simulation to the post-operative measurements.

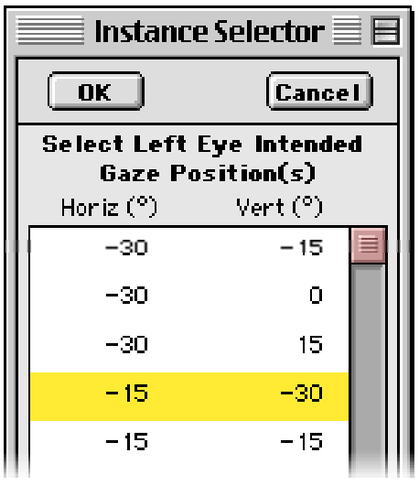
Avoid a Poor Treatment

(Note: to follow this section on your computer, you would need to advance your User Level to Experienced to gain access to the Mechanical State Viewer (see *Orbit Reference/ Preferences*, below). Alternatively, you could just read this section).

An SO tendon tuck might seem worth a try. Simulation shows, however, that shortening the LSO tendon by 10 mm corrects hypertropia in up- and level gaze, but gives little improvement of left eye depression in the important downgaze reading positions:

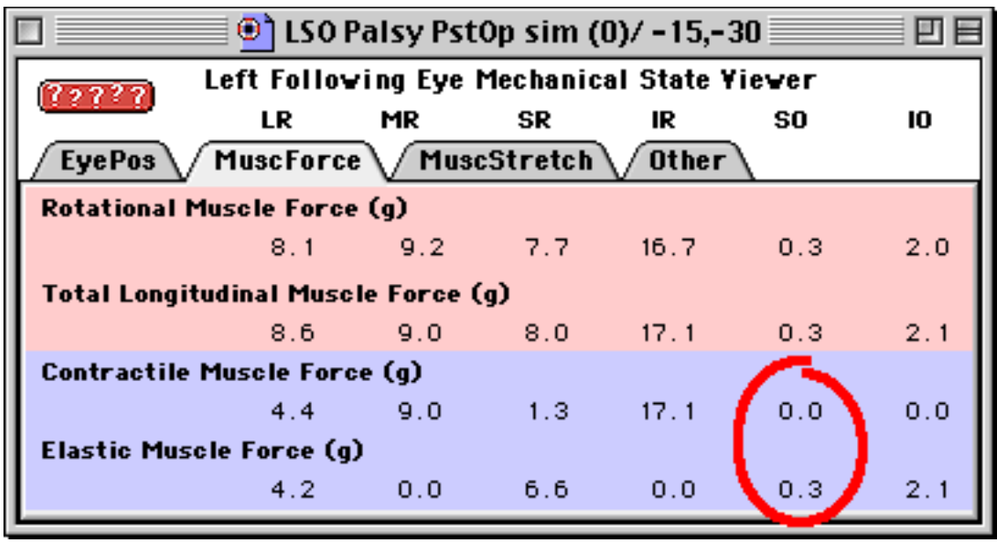


Orbit helps understand why this is a consequence of the SO's impaired contractility and normal elasticity.



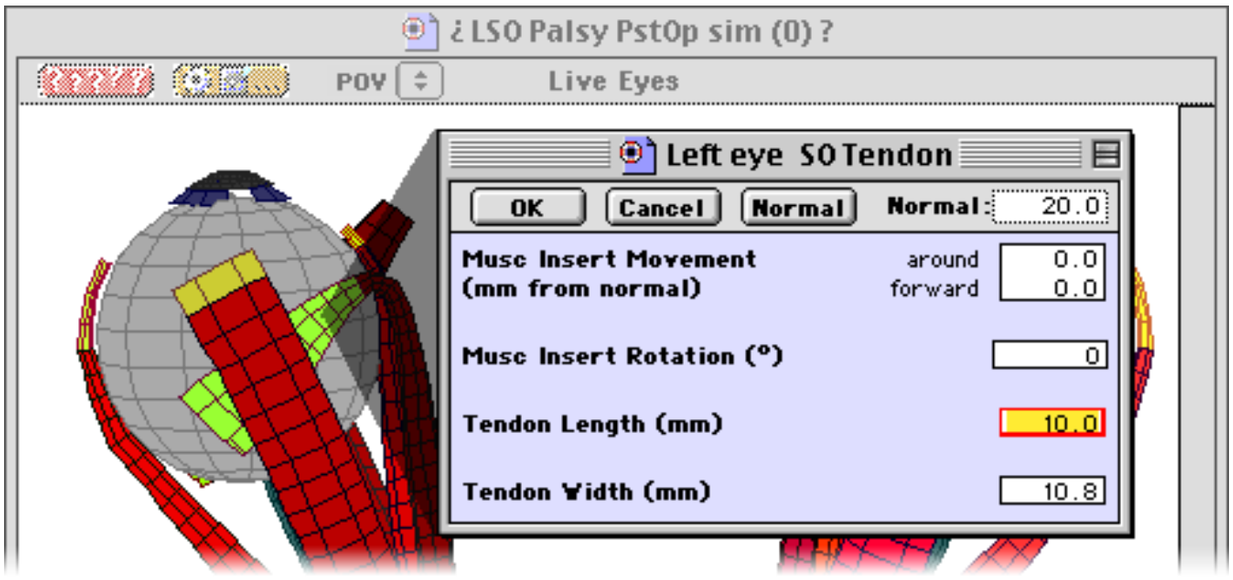
Before tucking the SO tendon, we opened » **Left Eye** » **Mechanical State Viewer**, and choose the most hyperphoric left eye downgaze position:

Downgaze, particularly in adduction, is the LSO's field of action: its elastic force is therefore always low, and here, is near zero. Its contractile force, because of the paresis is, of course, zero:


LSO Palsy PstOp sim (0)/ -15,-30
Left Following Eye Mechanical State Viewer
LR MR SR IR SO IO
EyePos MuscForce MuscStretch Other
Rotational Muscle Force (g)
8.1 9.2 7.7 16.7 0.3 2.0
Total Longitudinal Muscle Force (g)
8.6 9.0 8.0 17.1 0.3 2.1
Contractile Muscle Force (g)
4.4 9.0 1.3 17.1 0.0 0.0
Elastic Muscle Force (g)
4.2 0.0 6.6 0.0 0.3 2.1

Similarly, we opened the Mechanical State Viewer for upgaze and adduction (-15, 30), and saw that SO elastic force was 2.3 g.

Then, we used » **Both Eyes** » **Live Eyes** to tuck the SO, by changing the LSO tendon length from 20.0 mm to 10.0 mm:



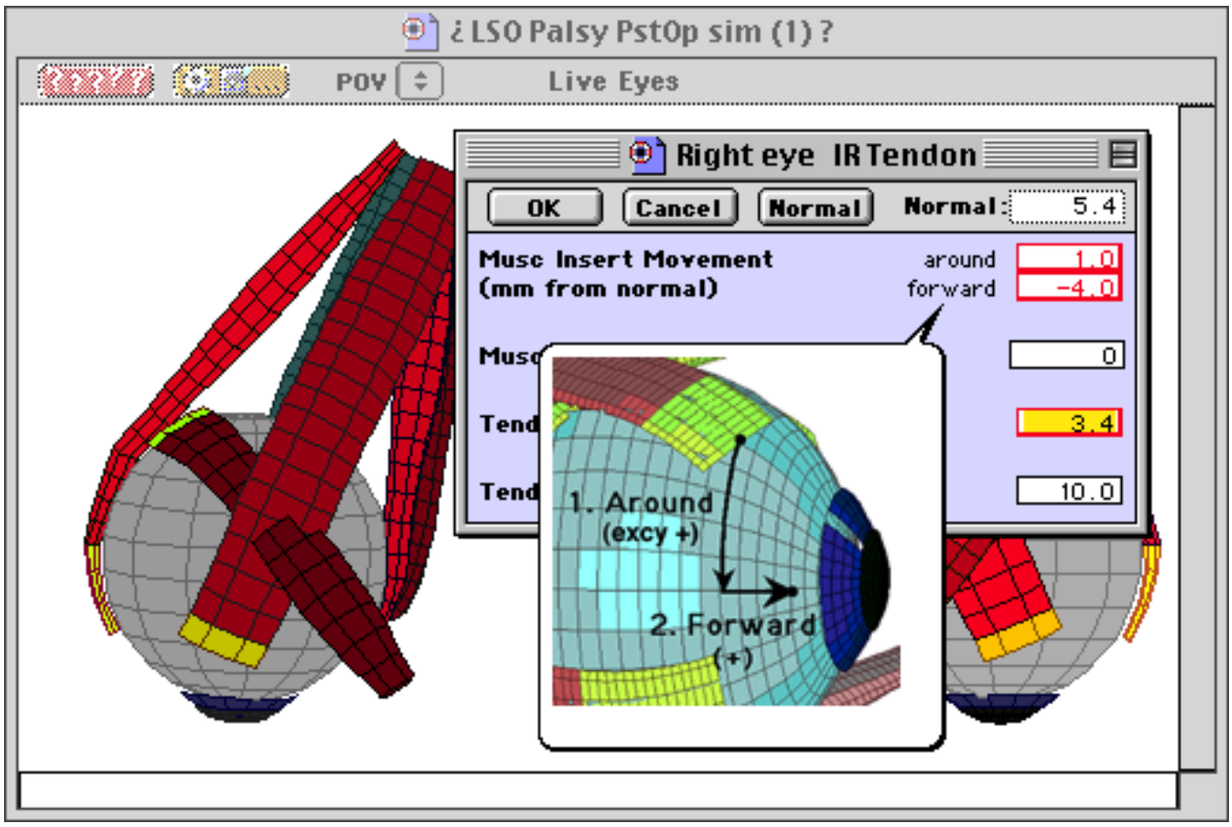
Looking again at the Mechanical State Viewers, we found that downgaze showed only a modest increase in LSO elastic force to 3.5 g, up from 0.3. This is why the tuck had little effect in downgaze. In upgaze LSO elastic force increases substantially to 9.5 g, up from 2.3 g, resulting in a larger corrective effect in upgaze.

Thus, we see that tucking the SO in this case should not be expected to correct reading positions, and why it should not. In a different case, the pre-operative simulation might have included LSO atrophy (abnormally low elastic force). In such cases, we would find that an LSO tuck also fails to correct upgaze.

Plan a Treatment (continued)

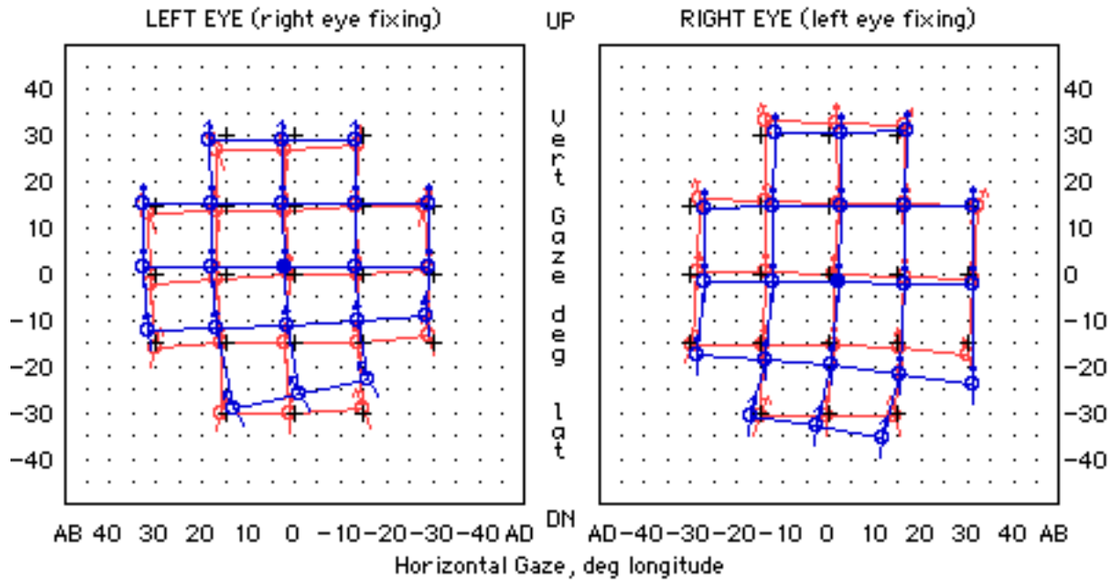
These patients actually were treated with RIR recession of about 4 mm and LIO myectomy or recession.

☞ Here is how to simulate the RIR recession. Continue from where you imported the post-operative measurements, or open LSO Palsy PstOp sim (0). Open the **Live Eyes** window, choose the Inferior point-of-view, and click the RIR tendon. The figure of the pop-up window below shows the Help Balloon, to remind you that movement "forward" is along a longitude line from the eye's posterior pole to its anterior pole, and movement "around" is along a perpendicular latitude line:

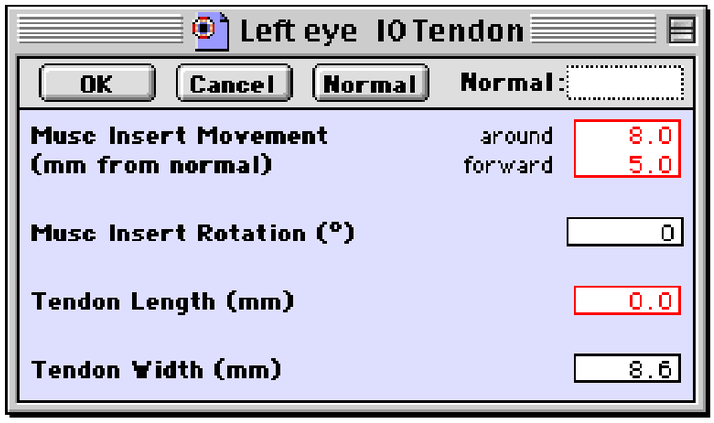


The Muscle Insertion Movement shown above is 4.1 mm, as reported by the surgeons. But we must also account for tendon lost during disinsertion and reinsertion. We estimate that 2 mm are lost, and reduce RIR tendon length from 5.4 to 3.4 mm.

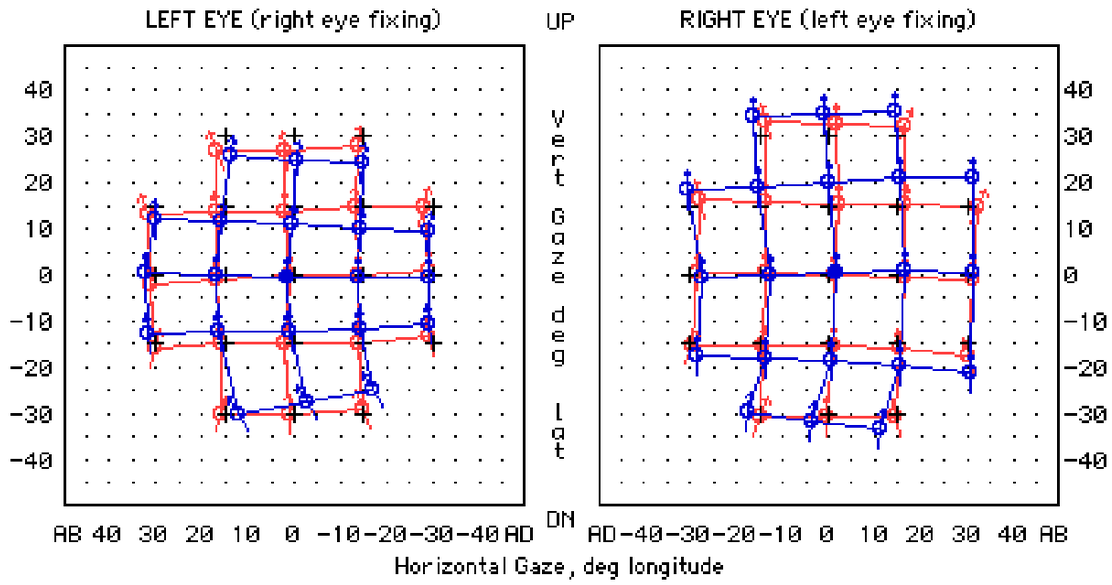
Compared to postsurgical measurements, the simulation is still left-hyperphoric, especially in downgaze (LSO Palsy PstOp sim (1)):



☞ To complete the postsurgical simulation, we need to simulate the LIO recession performed on these patients:



☞ Select » **File** » **Save As...** to name this simulation LSO Palsy PstOp sim(2):



Comparing simulation and post-operative measurements, we have a good match. The main discrepancy is the loss of vertical range in adduction. This is a plausible consequence of weakening both left obliques, and the mystery is really why clinical measurements do not show this effect. Further research would be necessary to determine whether this is due to central motor adaptation, poor clinical measurements (eg, incomplete binocular dissociation), or a problem in the model.

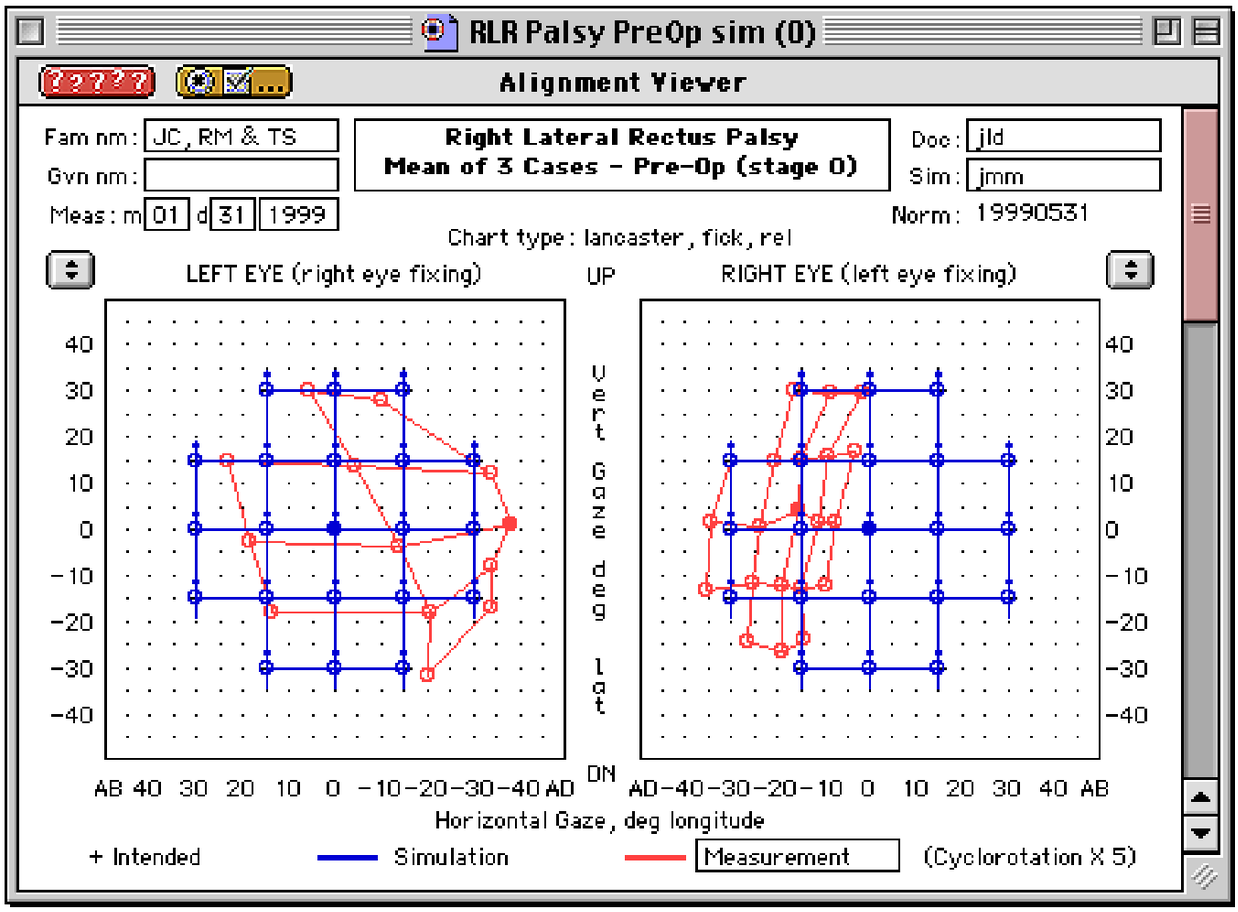
☞ Now, » **File** » **Close Simulation** to prepare for a new simulation.

Lateral Rectus Palsy

This is the simulation that suggested *soft rectus muscle pulleys*.

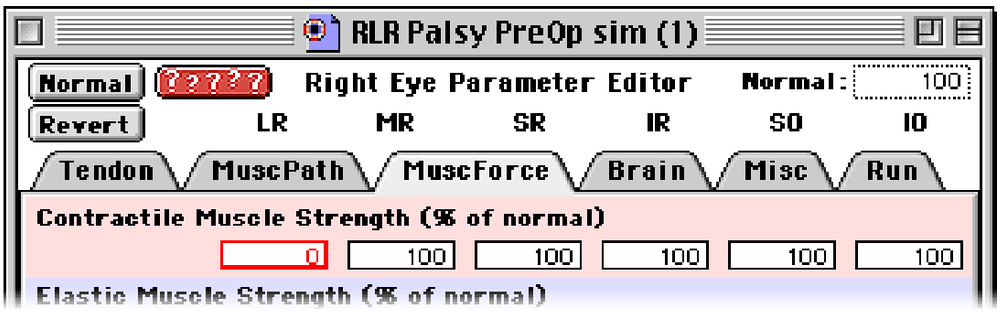
☞ To begin, raise your User Level to Experienced (select **» Both Eyes » Preferences for New Simulations**, click the Sim tab, and select Experienced). This will give you access to the Parameter Editor, and so, several parameters not available in the Live Eyes.

☞ Begin a new simulation with **» File » New**. Import the supplied measurements files RLR Palsy PreOp LE meas and RLR Palsy PreOp RE meas into the left and right eyes, respectively, and enter some identification:

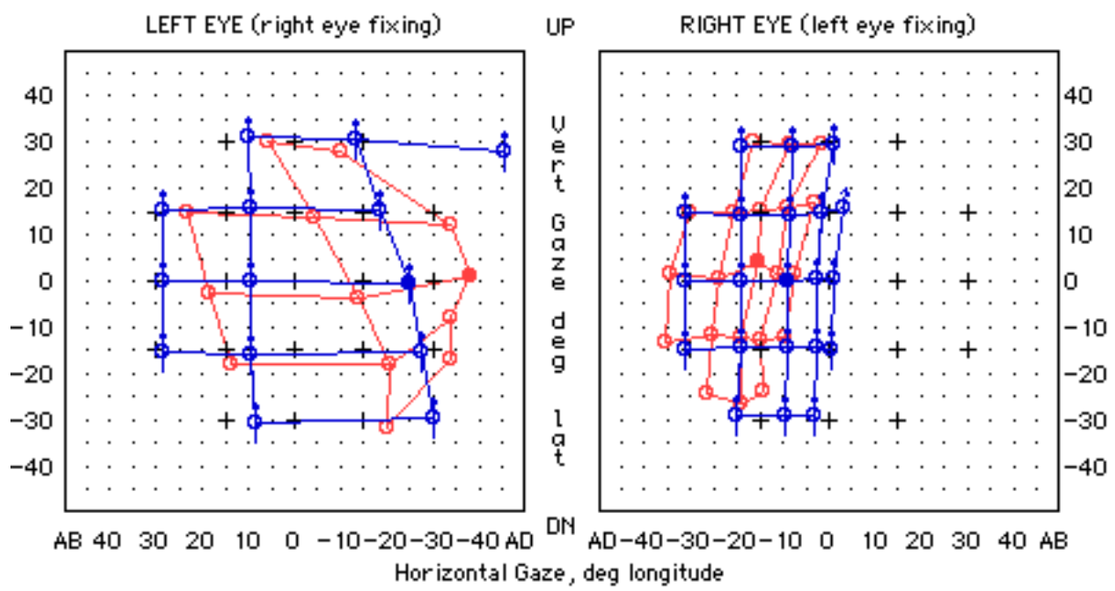

RLR Palsy PreOp sim (0)
Alignment Viewer
Fam nm: JC, RM & TS
Gvn nm:
Meas: m 01 d 31 1999
Right Lateral Rectus Palsy
Mean of 3 Cases - Pre-Op (stage 0)
Doc: jld
Sim: jmm
Norm: 19990531
Chart type: lancaster, fick, rel
LEFT EYE (right eye fixing)
UP
RIGHT EYE (left eye fixing)
40 30 20 10 0 -10 -20 -30 -40
Vert Gaze deg lgt
DN
AB 40 30 20 10 0 -10 -20 -30 -40 AD
AD -40 -30 -20 -10 0 10 20 30 40 AB
Horizontal Gaze, deg longitude
+ Intended
Simulation
Measurement
(Cyclorotation X 5)

☞ Select » **Right Eye** » **Parameter Editor**.

☞ The primary deficit in a complete RLR palsy is, by definition, the absence of RLR contractility, so set the RLR Contractile Muscle Strength to 0 (RLR Palsy PreOp sim (1)):


RLR Palsy PreOp sim (1)
Normal
????
Right Eye Parameter Editor
Normal: 100
Revert
LR MR SR IR SO IO
Tendon MuscPath MuscForce Brain Misc Run
Contractile Muscle Strength (% of normal)
0 100 100 100 100 100
Elastic Muscle Strength (% of normal)

In the saved file, we set Preferences to suppress alerts about "solutions not found". If you did not use this file, you might see such a message now. It simply refers to the fact that the paretic right eye could not fixate all the points we selected, and so corresponding right eye positions could not be found.


LEFT EYE (right eye fixing)
UP
RIGHT EYE (left eye fixing)
40 30 20 10 0 -10 -20 -30 -40
Vert Gaze deg lgt
DN
AB 40 30 20 10 0 -10 -20 -30 -40 AD
AD -40 -30 -20 -10 0 10 20 30 40 AB
Horizontal Gaze, deg longitude

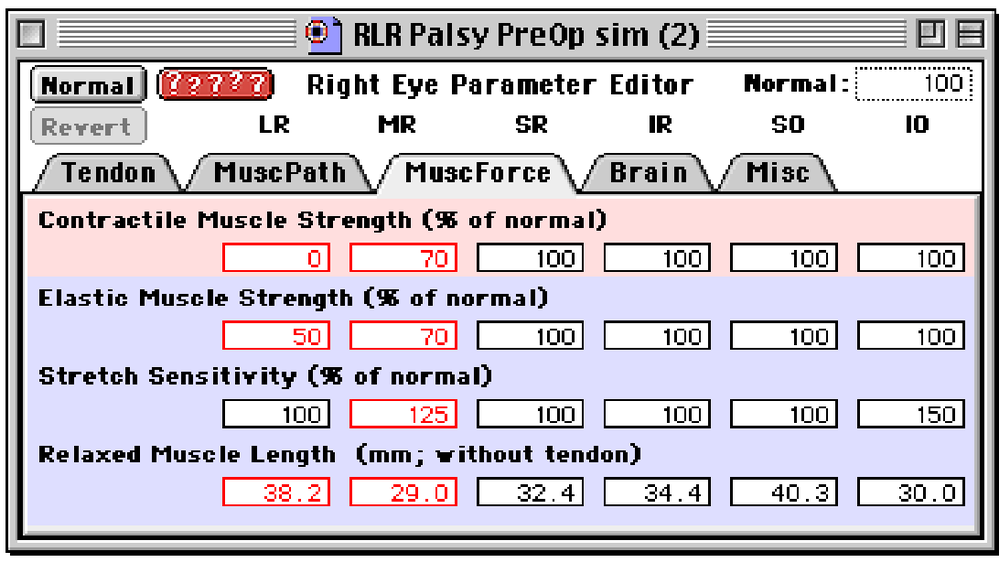
Estimating secondary changes takes some thought – and some guesswork, since we have only begun to characterize strabismus syndromes in biomechanical terms, and to develop ways to estimate parameters in individual patients (Demer and Kerman, 1994; Demer, et al, 1994; Demer, et al, 1995; Demer and Miller, 1997; Demer, et al, 1998; Demer, et al, 1999; Demer and Miller, 1999):

- We expect atrophy of a chronically paralyzed muscle (marked reductions in cross-section have been measured by MRI (Demer and Miller, 1995). Let's

estimate a 50% reduction in RLR Elastic Muscle Strength.

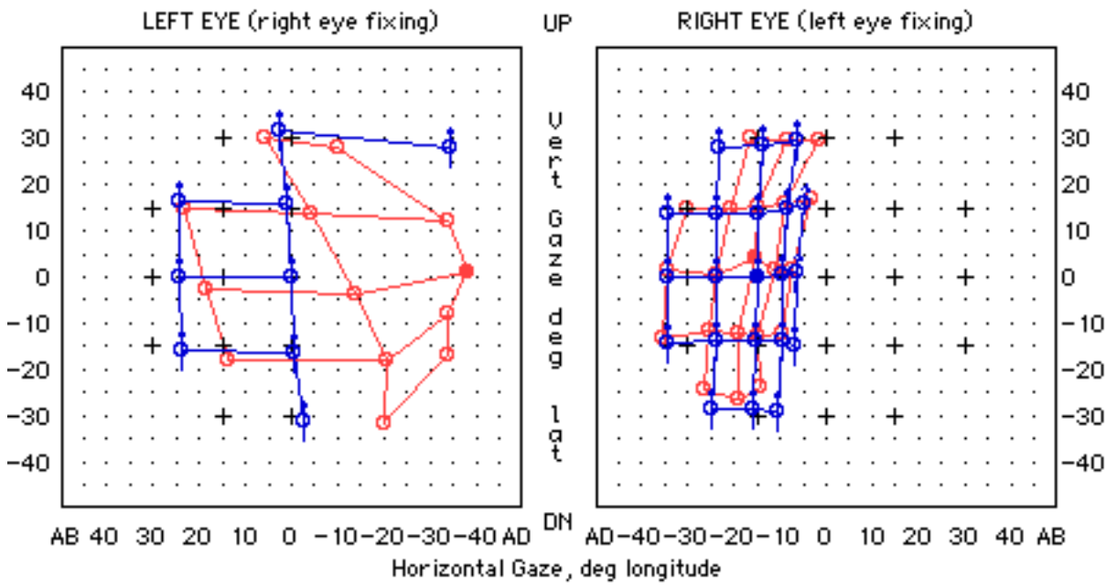
- Undoubtedly, the RLR will stretch. We estimate 2 mm of stretch, supposing that the muscle adapts to the eye's chronic esotropia.
- There is evidence that modest atrophy occurs in the antagonist of a paralyzed muscle. We model this by reducing RMR Contractile Muscle Strength and RMR Elastic Muscle Strength both to 70% of normal.
- The RMR, too, should adapt to its chronically reduced path length. We estimate it shortens 2 mm.
- Finally, we know that the antagonist of a chronically paralyzed muscle may become fibrotic, resisting elongation beyond what is due to its slight shortening. This is easily simulated by increasing RMR Stretch Sensitivity to 125% (see the section *Manipulating the Muscle Model*, above).

☞ Using the Right Eye Parameter Editor, make these secondary changes:



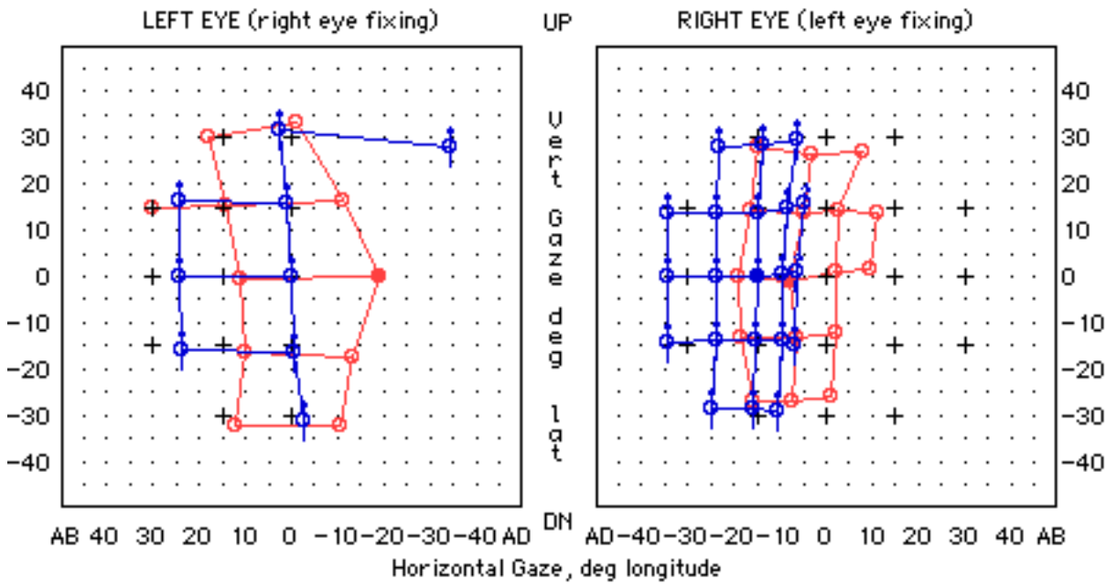
(Note: the unusual "normal" value of 150% for IO Stretch Sensitivity is an interim solution to the problem of not yet knowing how to model the IO with Lockwood's Ligament. With the usual 100% value, the IO exerts too little elastic force in downgaze).

☞ Then activate the Alignment Viewer (RLR Palsy PreOp sim (2)):



The right eye shows a typical esotropic pattern, with abduction not reaching the midline. Part of the left eye pattern is missing because of the paretic right eye's restricted range of fixation. Note, however, that the left eye measurements are more complete than the left eye simulation. This probably indicates a problem with the clinical measurements. Consider where the left eye intends to fix primary position (filled red dot in left panel above). This measurement should be the position of the following left eye, where the right eye fixes primary position. But from the right eye positions in the right panel, it appears that the right eye cannot get to primary position. If, by extreme effort, the patient did get his right eye to primary position, then the "secondary deviation" of the following left eye would probably be so large as to put the filled red dot on the left off the chart. Such subjective alignment measures as were used to collect these data give no indication of whether the fixing eye actually achieved the gaze angle requested, or if the subject just approached it as closely as he or she could. In the later case, the alignment measurements are invalid. For this reason, we disregard the 5 measurements in the rightmost column for the left eye.

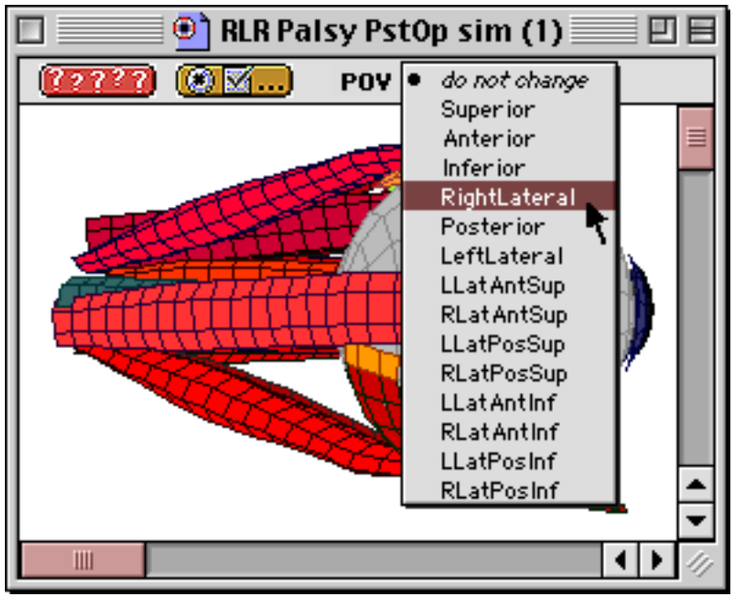
☞ As before, we begin the post-op simulation by comparing the final pre-op simulation with the post-op measurements (RLR Palsy PstOp sim (0)):



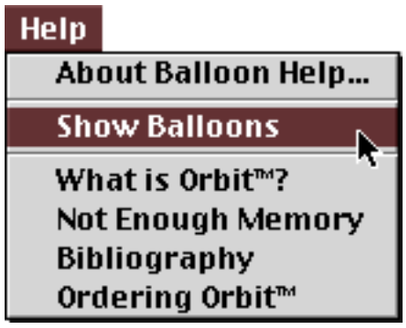
We will treat this chronic RLR palsy by transposing the vertical recti.

Transposition is best performed with the Live Eyes display, as the directions involved can be confusing*. With Live Eyes, simply adjust *forward* and *around* values until the picture looks right.

☞ Open Live Eyes and choose the Right Lateral point-of-view:

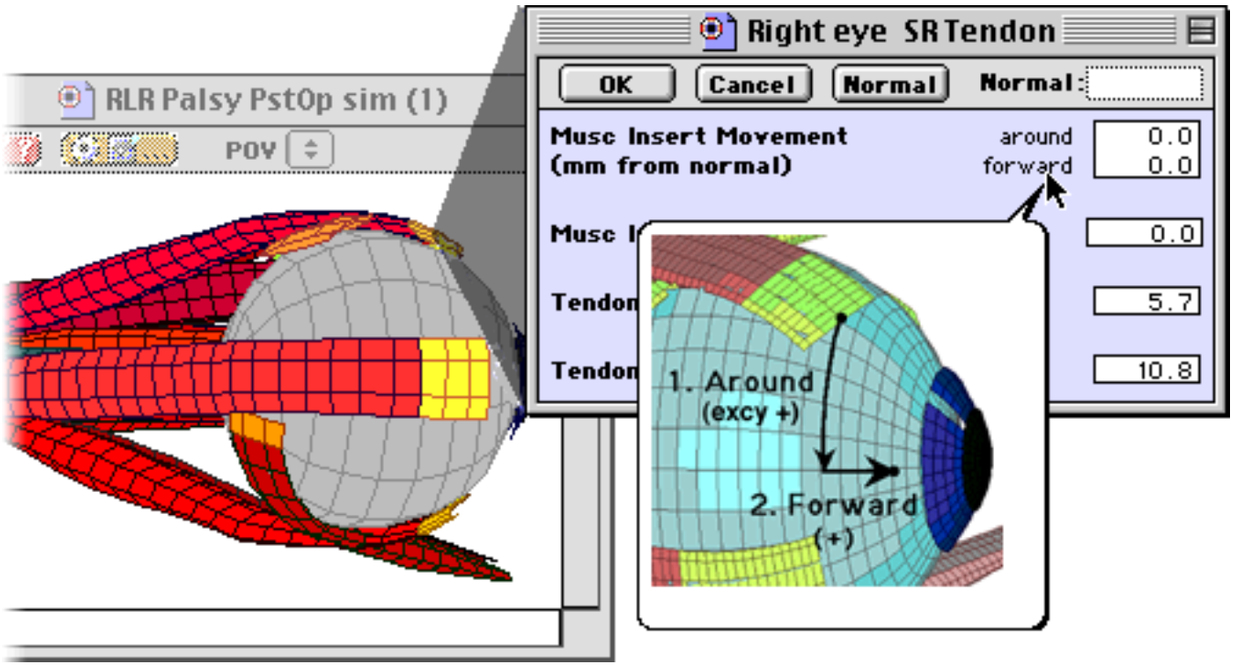


☞ To remind yourself about directions of insertion movement, turn on Balloon Help:

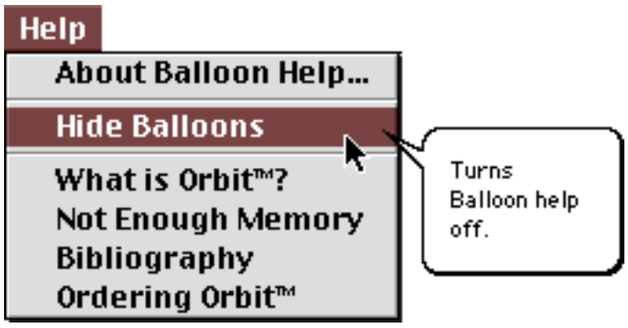


* If you insist on knowing: An *advanced* insertion moves along the line of muscle pull at the insertion, in such a direction as to stretch the muscle. A *transposed* insertion moves in a direction 90° clockwise from the direction of muscle pull, as viewed from outside the eye.

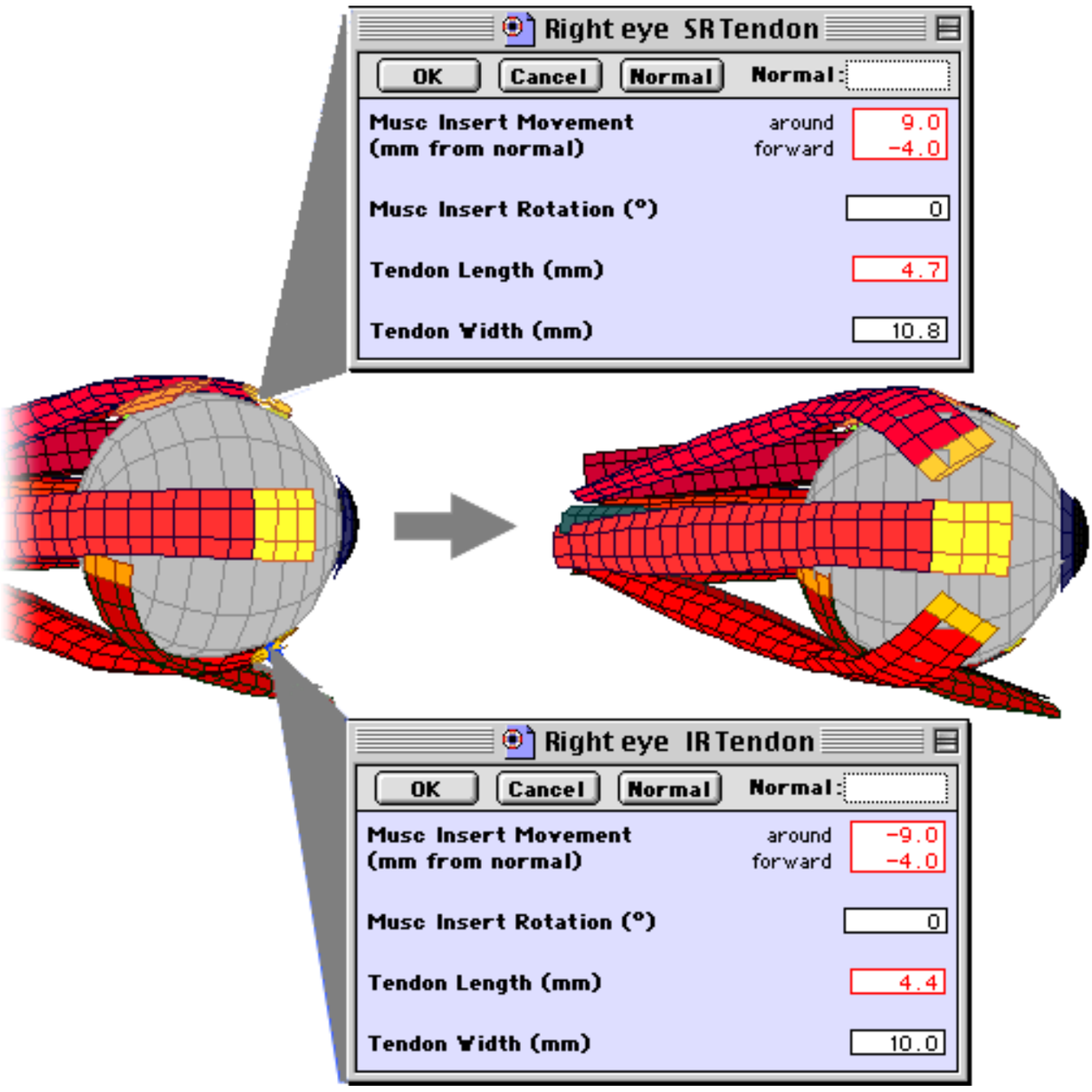
☞ Then click the RSR tendon:



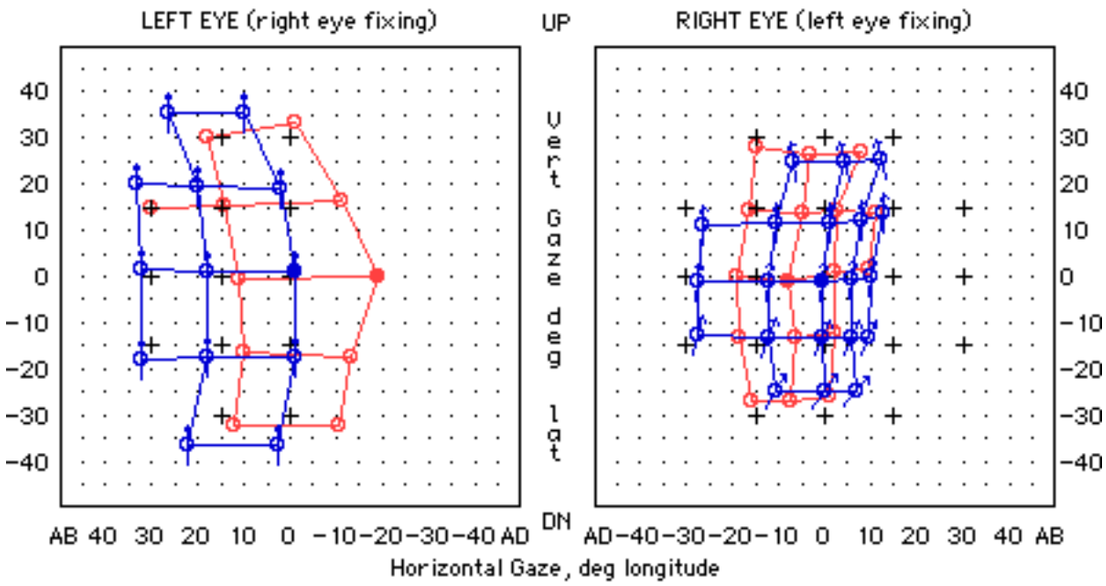
☞ Turn Balloon Help off:



☞ We're ready to do the RSR and RIR transpositions (note that we suppose 1 mm of tendon to be lost to the surgery):

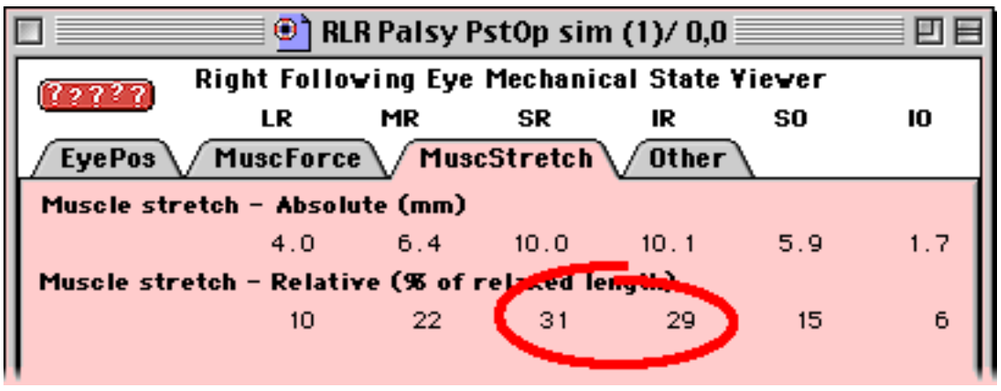


The resulting simulated alignment has the same "shape" as the measurements, but the simulation is relatively exotropic, and shows an asymmetry in left and right eye vertical range that is larger than that measured (RLR Palsy PstOp sim (1)):


LEFT EYE (right eye fixing)
UP
RIGHT EYE (left eye fixing)
Vert Gaze deg lat
DN
40 30 20 10 0 −10 −20 −30 −40
AB 40 30 20 10 0 −10 −20 −30 −40 AD
AD −40 −30 −20 −10 0 10 20 30 40 AB
Horizontal Gaze, deg longitude

Both of these inconsistencies should be reduced when we account for stretching of the transposed muscles. How much are the RSR and RIR stretched?

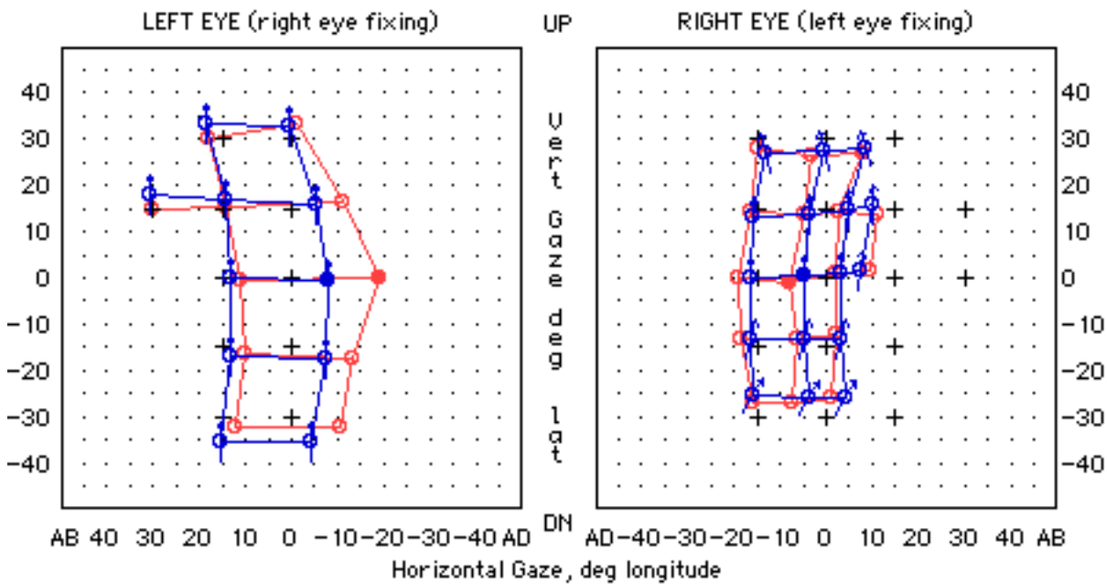
☞ Open » **Right Eye** » **Mechanical State Viewer** and select primary position (0, 0):


RLR Palsy PstOp sim (1)/ 0,0
Right Following Eye Mechanical State Viewer
LR MR SR IR SO IO
EyePos MuscForce MuscStretch Other
Muscle stretch - Absolute (mm)
4.0 6.4 10.0 10.1 5.9 1.7
Muscle stretch - Relative (% of relaxed length)
10 22 31 29 15 6

In a normal eye, the superior rectus muscle (SR) and the inferior rectus muscle (IR) are stretched only 15%, and we suppose that this represents the target of an EOM's length-adaptive processes.

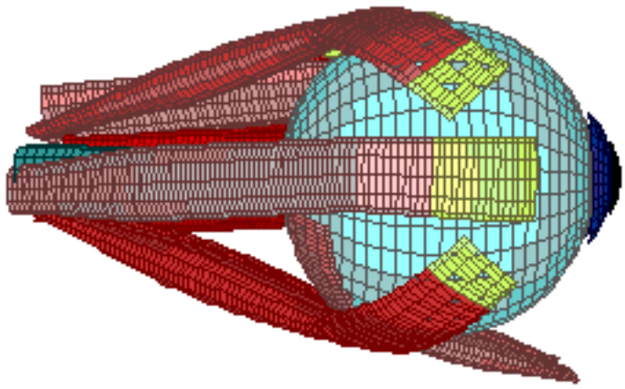
☞ Use the Right Eye Parameter Editor to increase RSR Relaxed Muscle Length (mm) from 32.4 to 36.6, and increase RIR Relaxed Muscle Length (mm) from 34.4 to 39.0. These changes restore RSR and RIR stretch to 15%. Finally, these patients got some additional procedures to improve horizontal alignment. We will simulate the botulinum injection given to one patient by changing RMR Relative Stretch Sensitivity from 125, representing "contracture", to 100%, representing a muscle that stretches normally.

☞ Finally, to facilitate comparison, we use **» Both Eyes » Gaze Selector** to remove from the simulation those gazes for which we do not have measurements (RLR Palsy PstOp sim (2)):



The simulation achieves a good match with the clinical measurements. Some improvement in right eye horizontal range has been achieved, although not enough to normalize primary position. As expected, some vertical range has been lost. The main clinical problem remaining is the primary position misalignment, which might have been better managed by transposing RSR and RIR with posterior sutures (Foster, 1996).

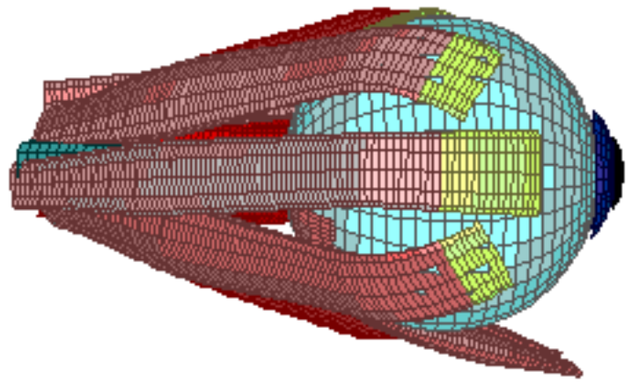
☞ We can visualize the post-operative eye with **» Right Eye » Graphic Eyes**. Here is the right-lateral view of the right eye, with the left eye fixing (0, 0):



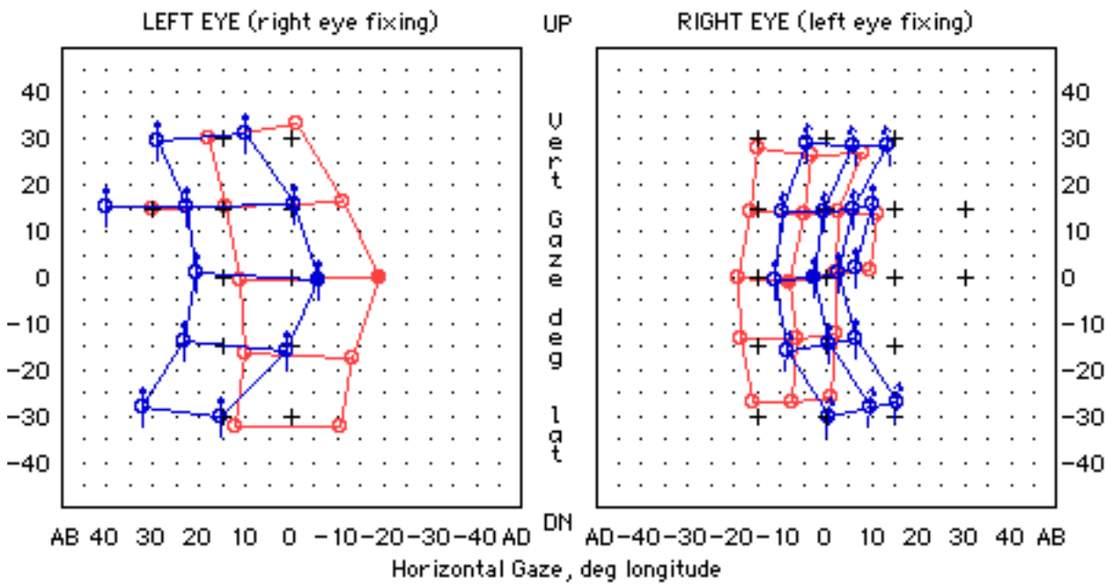
We began by mentioning that this simulation led to the discovery of *soft rectus muscle pulleys*. As shown above, the SR and IR pulleys hold the bellies of the transposed muscles near their pre-surgical paths.

What happens without pulleys?

☞ To eliminate pulleys from Orbit 1.8 (thereby making it behave in this respect like Orbit 1.0) we locate RSR and RIR pulleys at the muscle origins in the left eye, right eye and inner eye. (This requires the Expert User's Parameter Editor, which shows coordinates of the muscle origins). Without pulleys, the transposed muscles take shortest paths, which lie close to the RLR:



Such muscle paths are not observed in post-operative magnetic resonance images (Miller, et al, 1993). The resulting simulated alignment is both alarming and unphysiologic (RLR Palsy PstOp sim (no puleys)):



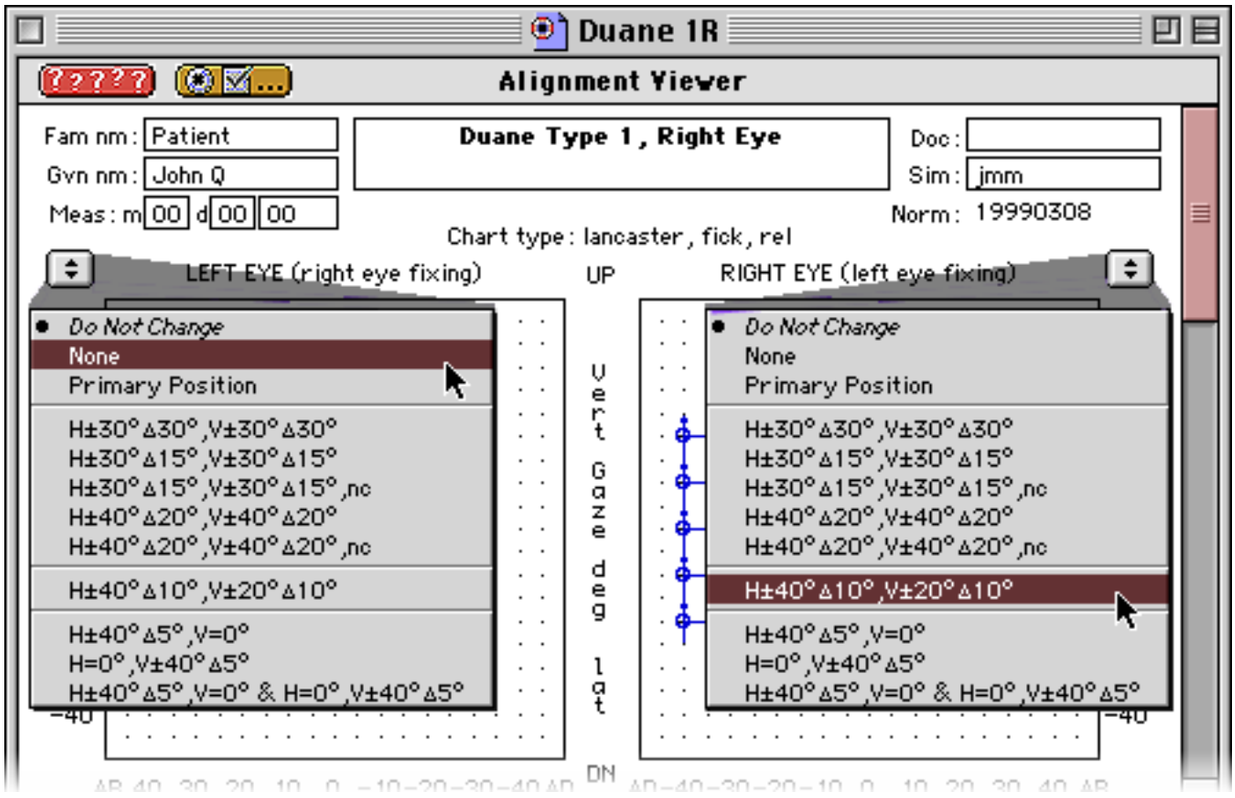
The significant difference between the simulations with and without pulleys is the strangely varying horizontal misalignment in the later. This occurs because, without pulleys, the transposed vertical recti acquire actions similar to the RLR, except they are innervated in up- and downgaze.

Duane's Retraction Syndrome

Following Huber (1970), von Noorden (1990) characterized three varieties of Duane's on the basis of clinical signs. Are there three corresponding mechanisms? Let's explore this question with some new simulations.

☞ To begin, check that your User Level is Experienced (select **» Both Eyes » Preferences for New Simulations**, click the Sim tab, and check that the Experienced button is pressed). The Parameter Editor provides a more convenient way than the Live Eyes to modify connections between motor nuclei and muscles. Click OK to confirm your changes.

☞ Begin a new simulation with **» File » New**, and set the following intended gazes:



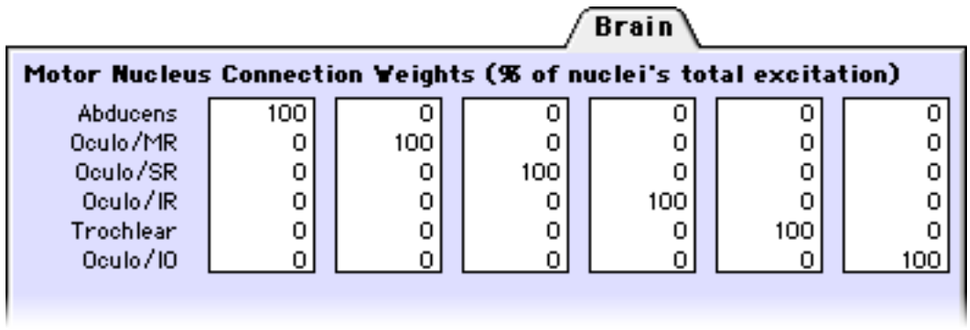
Type 1

The descriptive signs of Duane Syndrome Type 1 are:

1. Very limited or absent abduction.
2. Protrusion of globe on attempted abduction.
3. Normal or slightly limited adduction.
4. Globe retraction on adduction.
5. Frequently, up-shoots or down-shoots on adduction.

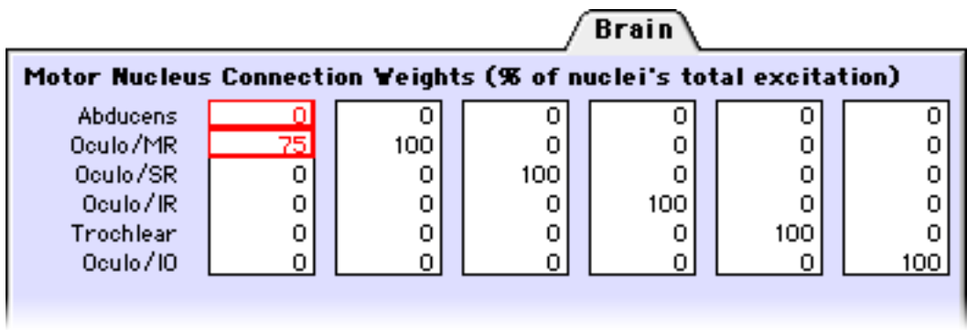
Signs 1 and 2, and of course the anatomic findings of Hotchkiss, et al (1980), suggest that the abducens nucleus is absent or non-functional. Signs 3 and 4 suggest that the MR branch of the oculomotor nucleus is providing partial innervation to the LR and, so, producing co-contraction.

☞ Choose » **Right Eye** » **Parameter Editor**, and click the **Brain** tab:


Brain
Motor Nucleus Connection Weights (% of nuclei's total excitation)
Abducens 100 0 0 0 0 0
Oculo/MR 0 100 0 0 0 0
Oculo/SR 0 0 100 0 0 0
Oculo/IR 0 0 0 100 0 0
Trochlear 0 0 0 0 100 0
Oculo/IO 0 0 0 0 0 100

The normal connection matrix, above, shows each muscle fully innervated by "its" motor nucleus or sub-nucleus (weight of 100%), and not innervated by any of the other 5 nuclei (weights of 0%). Think of these connection weights as applied to the motor neurons or at the neuromuscular junction. That is, nothing about the fixing eye, or about yoked or antagonistic muscles is directly changed by changing a connection weight.

Our theory of Duane's Type I may be expressed as follows:

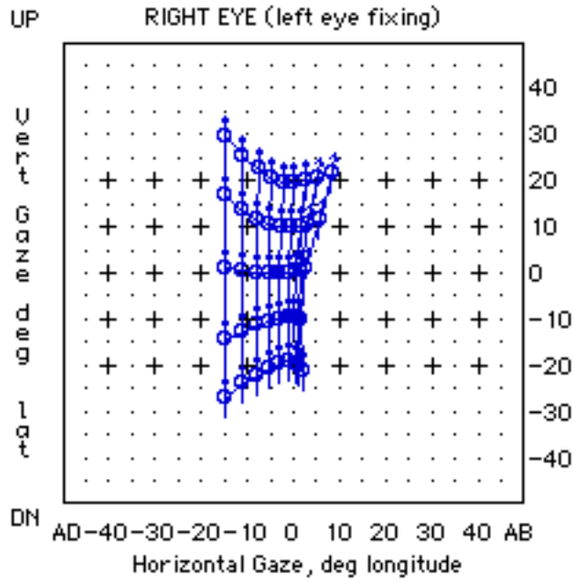

Brain
Motor Nucleus Connection Weights (% of nuclei's total excitation)
Abducens 0 0 0 0 0 0
Oculo/MR 75 100 0 0 0 0
Oculo/SR 0 0 100 0 0 0
Oculo/IR 0 0 0 100 0 0
Trochlear 0 0 0 0 100 0
Oculo/IO 0 0 0 0 0 100

Note the "shadows" on the two modified cells. A cell is shadowed when you modify it (either by typing a new value or clicking Normal). Shadows are retained until you depart from the window, and indicate which values would be affected by clicking Revert.

☞ A look at the Alignment Viewer shows that the rotational defects of Duane's Type I (signs 1, 3, and 5, above) are all reflected in the simulation:

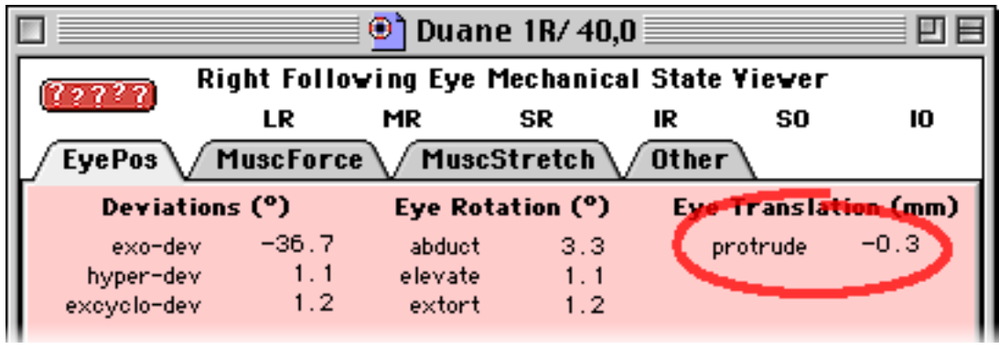
Note that up-shoots and down-shoots emerge naturally from co-contraction in adduction, essentially in accord with the theory advanced by Souza-Dias (1976).

Does the pattern of globe retraction also fit clinical expectations?



☞ Select » **Right Eye** » **Mechanical State Viewer**, and open the windows for intended gazes (–40,0), (–20,0), (0,0), (20,0), and (40,0) -- you can select them all at once by holding down the ⌘ key as you click on items in the list (you'll need to scroll the window to select them all):

☞ Click OK to get a cascade of windows, one for each fixing eye position, containing values for globe protrusion under the EyePos tab. As usual, the title bars of the Mechanical State Viewers are labeled with the intended gaze position of the following eye, that is, the position a normal following eye would have gone to. For example, the intended gaze {40,0} corresponds to fixing eye gaze {-40,0}, because when the fixing eye adducts (negative) the following eye abducts (positive).



The title of this window indicates that a normal following eye would have been 40° in abduction (40,0), and gives the values for the sick following eye: it's highly eso- and slightly hyper-deviated, and shows 0.3 mm of globe retraction.

A reasonable way to evaluate globe translation is in comparison to the normal eye:

Intended Horizontal Gaze	Normal Eye Protrusion	Duane's I Eye Protrusion	Duane's I Relative Protrusion
-40	-0.7	-1.3	-0.6
-20	-0.5	-0.8	-0.3
0	-0.5	-0.4	+0.1
20	-0.6	-0.3	+0.3
40	-0.9	-0.3	+0.6

So, with respect to globe translation, our simulation predicts the expected pattern: retraction (negative protrusion) in adduction and protrusion in attempted abduction. However, the total range of abnormal axial translation, just over 1 mm, seems a bit small. Should you wish to pursue this simulation further, you might advance to Expert Level, which allows you to modify Globe Translational Stiffness. We think it reasonable to guess that a chronic co-contractive syndrome would soften the encapsulated fat pads that control globe translation. Reducing Globe Translational Stiffness greatly increases the magnitudes of retraction and protrusion.

Type 2

The signs of Duane's Type 2 are:

1. Normal or slightly limited abduction
2. Limited or absent adduction
3. Globe retraction on attempted adduction
4. Frequently, up-shoots or down-shoots on adduction

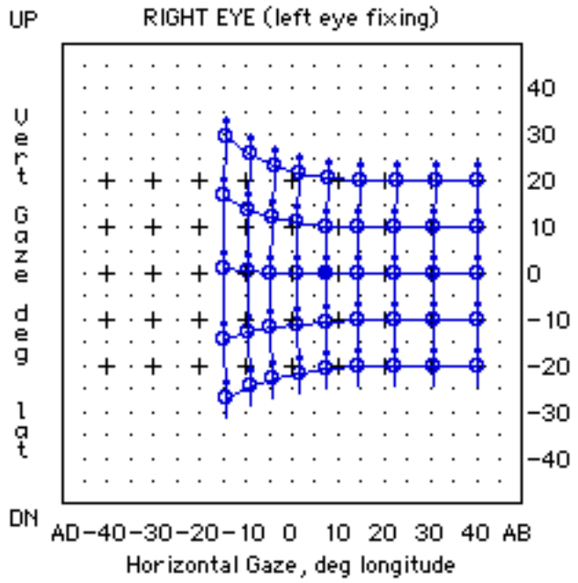
Our theory is that abducens innervation of LR is normal (sign 1), but that the MR branch of the oculomotor nucleus is providing partial innervation of LR (signs 2, 3 and 4). One change to the Connection Matrix ...

Brain

Motor Nucleus Connection Weights (% of nuclei's total excitation)

Abducens	100	0	0	0	0	0
Oculo/MR	75	100	0	0	0	0
Oculo/SR	0	0	100	0	0	0
Oculo/IR	0	0	0	100	0	0
Trochlear	0	0	0	0	100	0
Oculo/IO	0	0	0	0	0	100

... results in the following Alignment Chart:



Type 3

Duane's Type 3 is characterized by:

1. Limited or absent abduction
2. Limited or absent adduction
3. Globe retraction on attempted adduction
4. Frequently, up-shoots or down-shoots on adduction

We leave this simulation as an exercise for the reader.

Orbit Reference

Here, following some general comments on Orbit windows, we provide complete descriptions of each.

Two Types of Windows

Does the window have an OK button? If so, you must finish your work there and close it before doing anything else.

Most windows, however, don't have OK buttons, and it is convenient to leave several of them open on your desktop. We leave open Live Eyes or Parameter Editor (for trying different lesions and procedures), Alignment Viewer (to see the overall results), and Mechanical State Viewer (for corresponding numeric values).

Orbit windows (except the Parameter Fitter) know about each other: if you make a change (eg, with the Parameter Editor), all dependent windows (eg, the Alignment Viewer & Mechanical State Viewer) will know that they are out of date. For efficiency, however, we do not update background (ie, dim) windows until they are brought into the foreground. To remind you that the values in a background window may not be current, inverted and upright question marks (¿ ... ?) are placed around the simulation name. If you select an out of date window (eg, by clicking it to bring it into the foreground) it will update, and the question marks will disappear.

Preferences

There are three types of settings with which you can customize the behavior and appearance of Orbit and simulations you create. They differ in "scope":

- **Preferences for New Simulations** can be set to customize subsequently created, new simulations. These preferences are saved in the file Orbit_Prefs, which is associated with the Orbit application. Thus, these preferences remain in effect for a given copy of Orbit, until you change them (or trash the Orbit_Prefs file).

- **Preferences for Active Sim *sim_name*** contains many of the same settings, but only affects the currently active simulation. These preferences are saved are saved in the simulation file, and, so, re-assert themselves only when that simulation is opened.

- Finally, several windows offer Window Settings buttons, , which can be used to quickly and temporarily override the preferences for that window only. These are described in connection with individual windows.

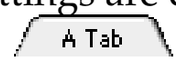
The Preferences window » **Both Eyes** » **Preferences for New Simulations**) lets you to customize simulations that you subsequently create (using » **File** » **New**). The Preferences window » **Both Eyes** » **Preferences for Active Sim *sim_name*** lets you customize the simulation that is currently active. The contents of the two preferences windows are similar.

Offers this explanatory page.

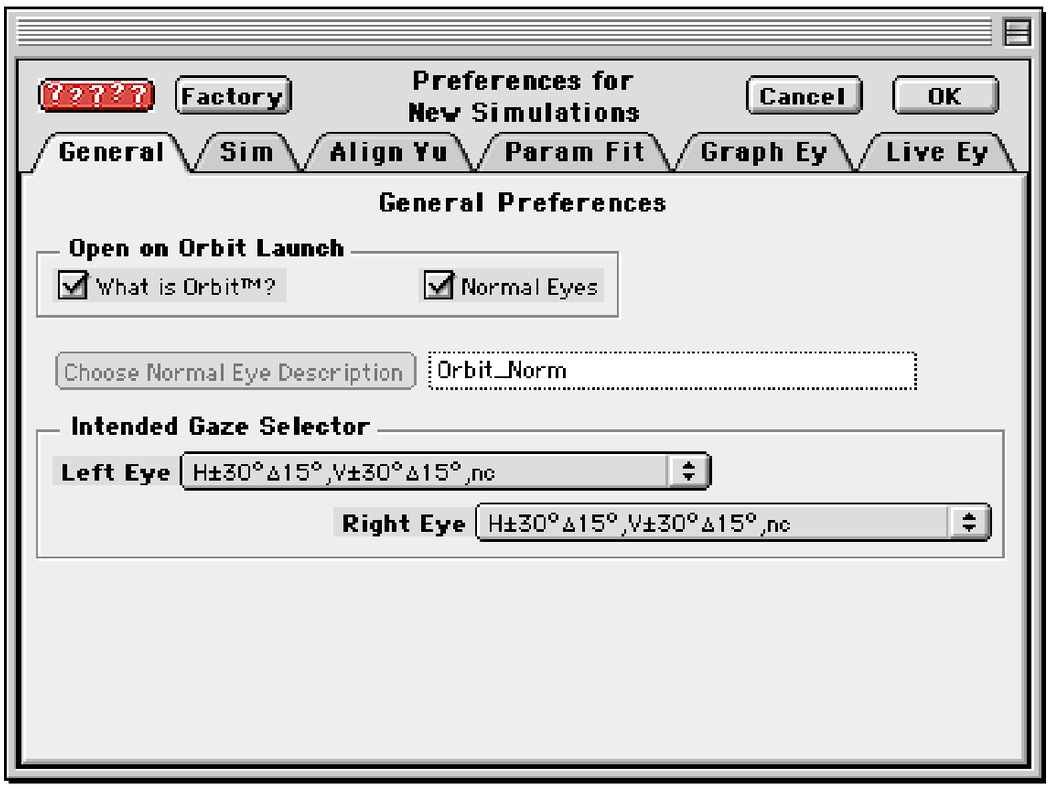
Returns all preferences to factory settings.

Closes the preferences window, ignoring any changes you might have made.

Accepts settings and closes the window.

Settings are divided into groups, each group attached to  .

The **General** preferences tab appears only in **Preferences for New Simulations**. **General** preferences are settings not specific to any single simulation or window:



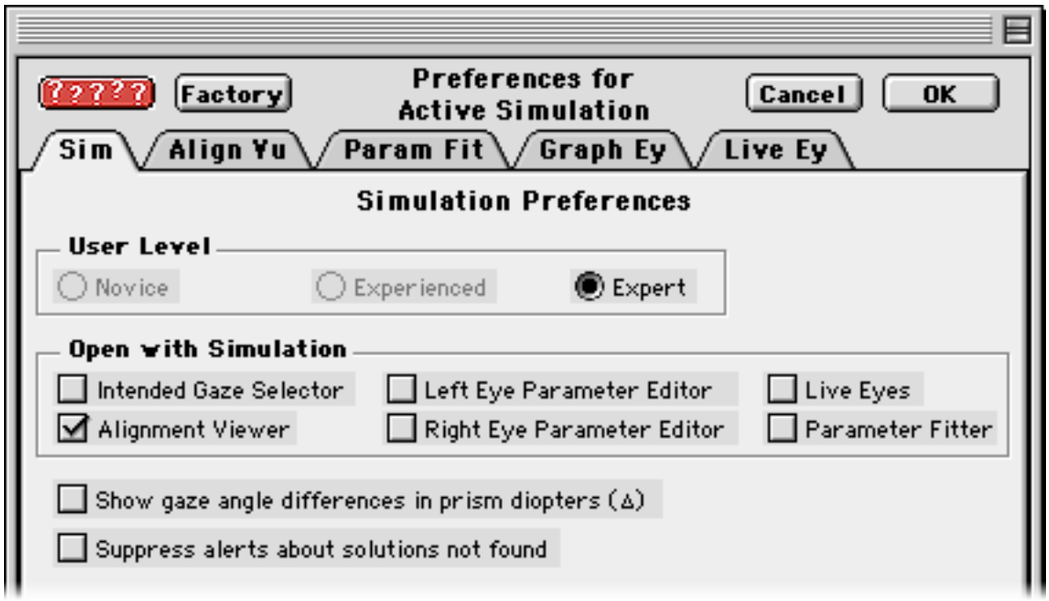
Open on Orbit Launch. These check-boxes determine what happens when the program is launched by double-clicking on the Orbit icon. It seems reasonable to begin a new Normal Eyes simulation, since if you had wanted to begin with a particular existing simulation, you could have double-clicked on that simulation. A new user will benefit from having the **What is Orbit™?** window open, but will soon want to deselect it.

Choose Normal Eye Description allows you to create simulations based on alternative normal eyes that you create. (Sorry, not implemented in version 1.8).

Intended Gaze Selector sets the gaze angles in a new simulation.

All other tabs appear in both preferences windows.

The **Sim** tab contains preferences that apply to an entire simulation:



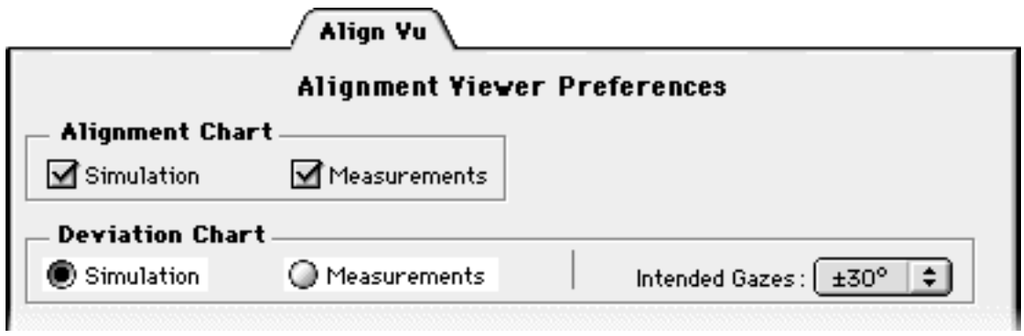
User Level. At lower User Levels, options are limited, to highlight basic operations. Novice users are not offered certain windows at all (they are dimmed in the Menu Bar); others appear in simplified form. Experienced users are offered all windows, but three of them, the Measured Gaze Editor, Mechanical State Viewer, and Eye Parameter Editor, appear in simplified forms. Almost all users of Orbit will begin at the Novice, and then advance to the Experienced level. (It is not allowed to lower the User Level of an existing simulation, because this could make inaccessible some values previously modified).

Open with Simulation. Have the windows you always use open automatically. On a slow machine it may take significant time to open large or graphic windows, and windows that require the simulation to update.

Show gaze angle differences in prism diopters. This will appropriately change the deviation values shown in various windows and their unit labels.

Suppress alerts about solutions not found can be checked if you don't wish to be notified when one or more gaze angles fail to converge.

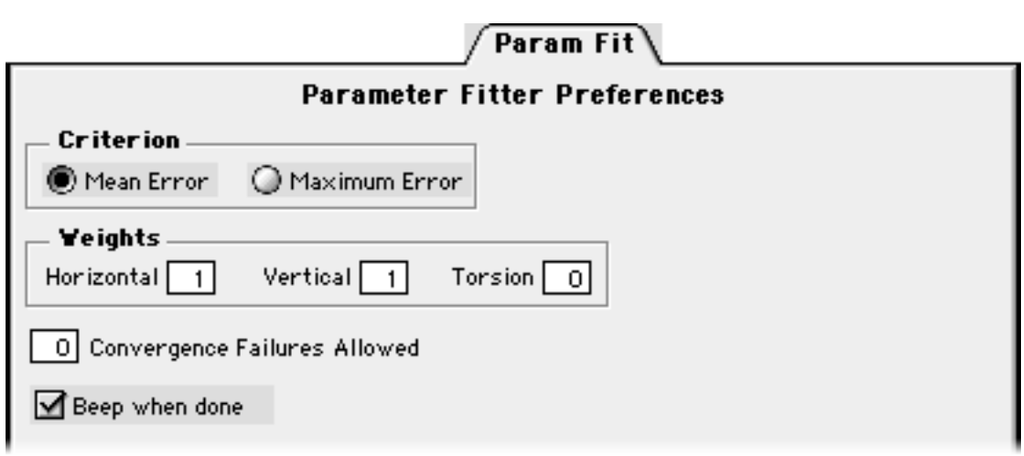
The **AlignVu** tab contains preferences for the Alignment Viewer window (» **Both Eyes** » **Alignment Viewer**):



Near the top of the Alignment Viewer is a Hess-Lancaster-type Alignment Chart, which always shows intended gazes (+), and optionally shows simulated positions of the following eye (blue **o**), and measurements (red **o**).

Below the Alignment Chart is the "tic-tac-toe" Deviation Chart. Deviations are differences between actual and intended gaze positions. Choose whether to view simulated deviations of the following eye, or measured deviations. Choose which deviations to show, by their intended gaze. If you have not selected some chosen positions with the Intended Gaze Selector, the chart will show blank boxes.

The **Param Fit** tab contains preferences for the **Parameter Fitter** window (» **Both Eyes** » **Parameter Fitter**) that allow you to modify the fitting method:



Choose the Mean Error **Criterion** if you want the best overall fit across all gaze positions for which measurements have been entered (this might allow a few badly fitted positions, but is usually the best choice). Choose the Maximum Error Criterion if you want the worst fitted position to be as good as possible.

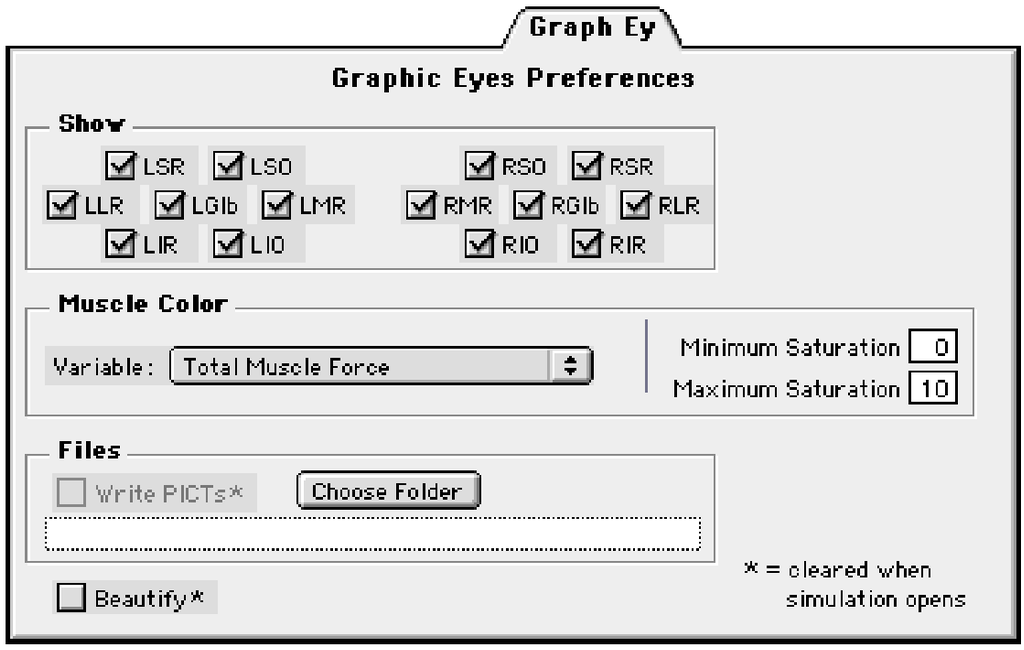
Weights are values from 0 to 10 which determine the relative (ie: 1,1,1 is the same as 10,10,10) significance of

each gaze angle component in the fitting algorithm. A weight of 0 means that the component is ignored in calculating the error that is minimized. Thus, because torsion measurements can be unreliable, its weight is often set to 0. If the torsion component is omitted from a measured gaze point it is, of course, omitted regardless of the weight.

It is possible for the Parameter Fitter to try eye parameters that Orbit cannot solve for some gaze angles. This may mean parameters are unrealistic, measurements are inaccurate (or Orbit is flawed). You may wish to allow a small number of **Convergence Failures** so that you can proceed.

Set **Beep when done** to be prompted when a fit is achieved. Fitting will take longer if you choose parameters from both eyes, many parameters, or many gaze angles.

The **Graph Ey** tab contains preferences for the **Graphic Eyes** window:



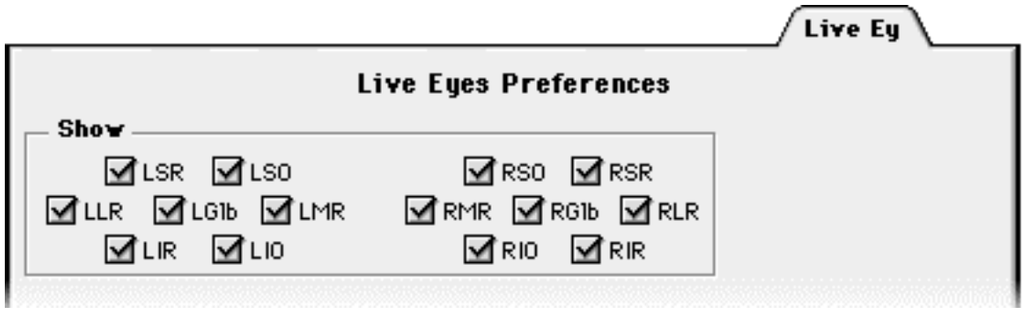
Show. The structures selected are shown.

Muscle Color. The saturation (purity) of the red muscle color is an index of the chosen Variable. Pure red indicates the value you enter in Maximum Saturation, and gray, the value in Minimum Saturation.

Files. Choose to write each Graphic Eyes window produced as a "PICT" type file in the folder specified. Orbit movies are made using a sequence of such PICT files. Note that if you leave this box checked unintentionally, you will create many unwanted PICT files!

Checking **Beautify** increases the resolution of the drawing.

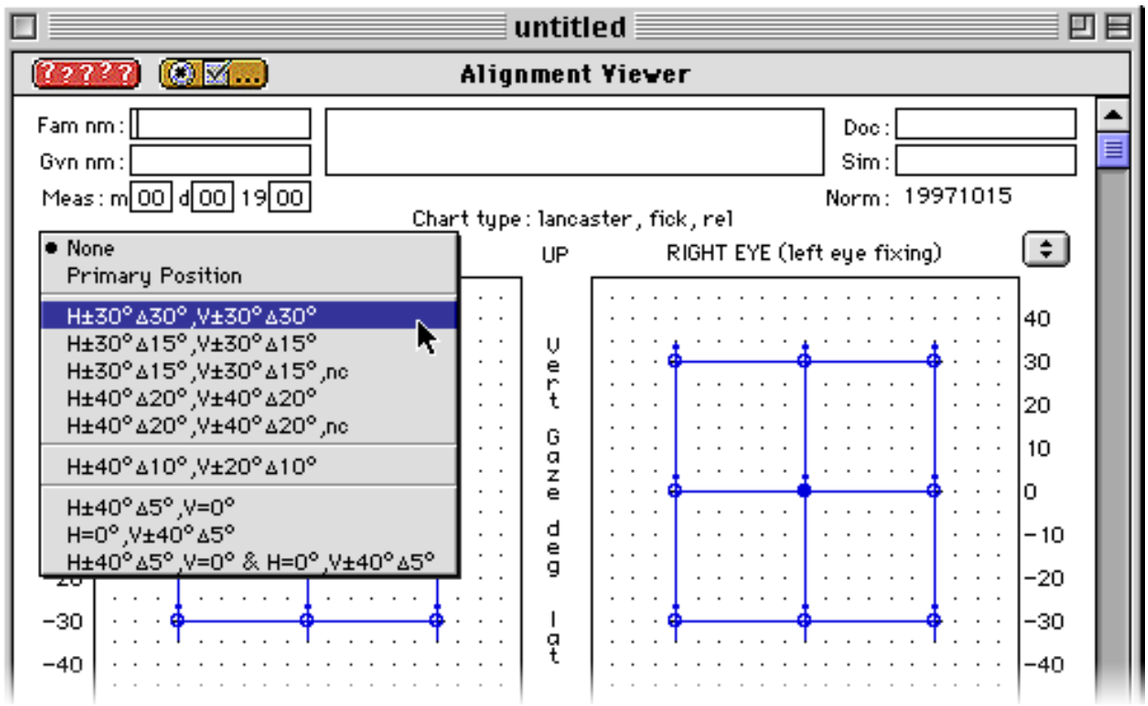
The **LiveEy** tab contains preferences for the **Live Eyes** window:



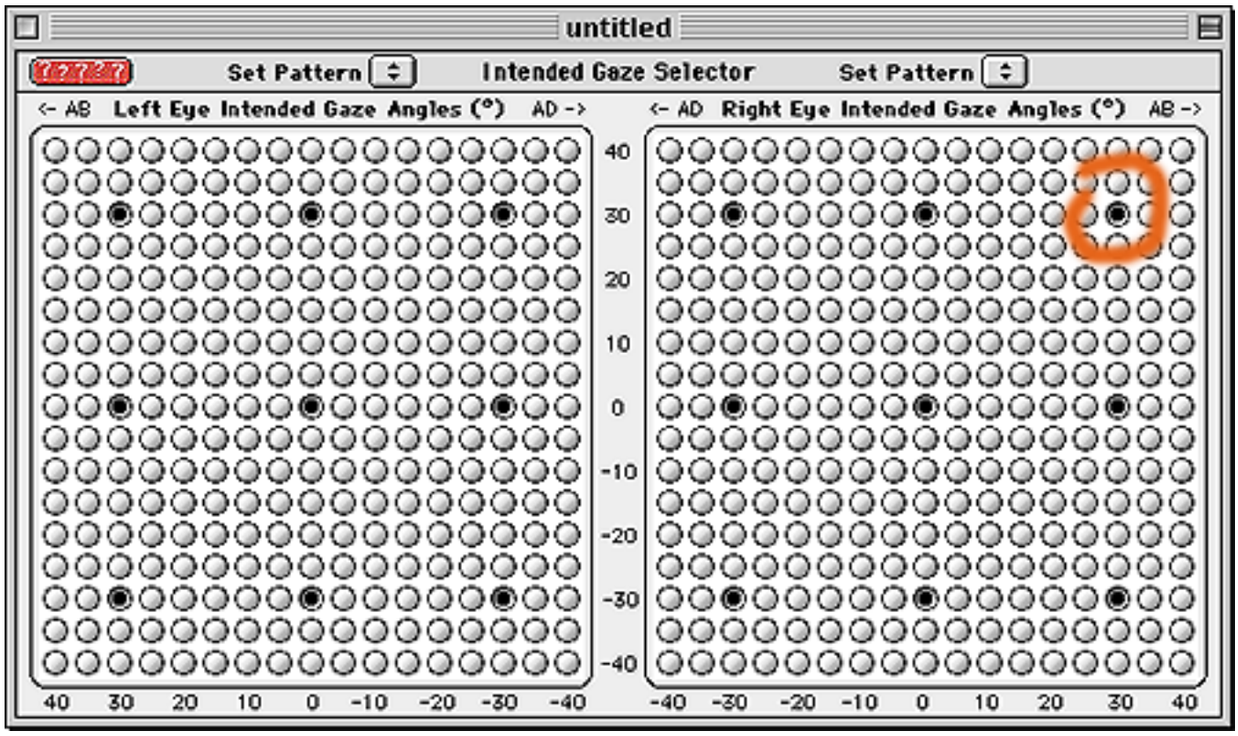
Show. The structures selected are shown.

Intended Gaze Selector

It is not necessary to use the Intended Gaze Selector (in fact, it is not available to Novice Users). Gaze angles can be set by choosing an item from the Set Pattern popup list in the Alignment Viewer:



Experienced and Expert Users can choose gaze patterns not available in the Set Pattern popup list by opening » **Both Eyes » Gaze Selector:**



The main part of the window consists of two panels containing buttons; click on these buttons to choose the

gaze angles to which each simulated eye attempts to rotate (moving "under cover").

Intended gaze positions of the left eye are chosen on the left, and those of the right eye on the right, following the perspective of the Alignment Chart. Abducting and adducting directions are as labeled near the top of each panel (the nose is between the two panels). All angles are in degrees.

Consider, eg, the gaze position for which the right eye will attempt to abduct 30° and elevate 30°. In terms of the Hess-Lancaster test, this means that the patient will be instructed to adduct 30° and elevate 30° with the fixing left eye. If both eyes are normal, the following right eye will go to the intended positions exactly. Otherwise, it may go somewhere else.

Remember that to Import clinical measurements (**» Left Eye » Import Measurements** or **» Right Eye » Import Measurements**), the intended gaze angles must already be in the simulation, eg, chosen in the Intended Gaze Selector.

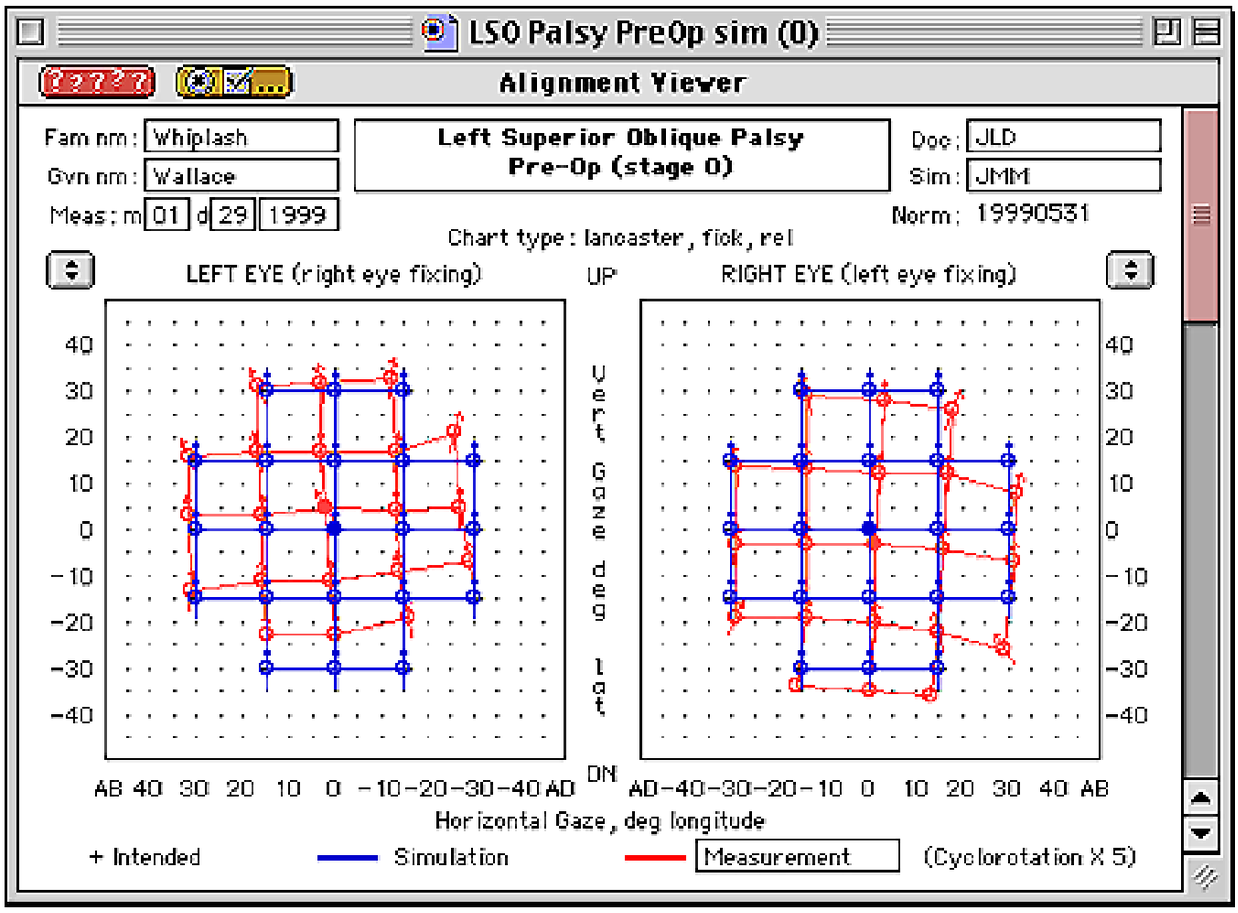
Alignment Viewer

Use the Alignment Viewer to view simulation results and measurements.

Info Fields

The top part provides fields to record patient and simulation information, and shows the *alignment chart*.

Help balloons (» **Help** » **Show Balloons**) associated with the patient and simulation information fields suggest how these fields may best be used.

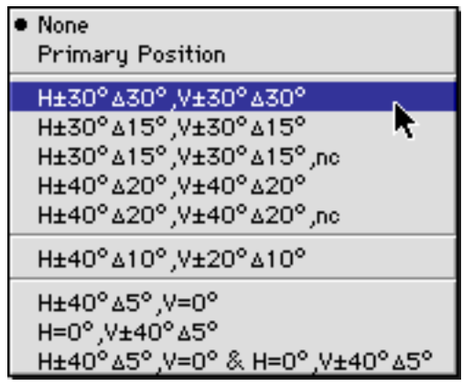


Alignment Chart

Below the information fields is a Hess-Lancaster-type *alignment chart.* The orientation of the chart follows clinical convention, with positions of the following (ie, "moving under cover") left eye on the left, and that of the following right eye on the right.

Each *intended gaze position* is represented as a small black cross, "**+**". The *intended gaze position* of a following eye is the position it would assume if the

whole system were normal. Equivalently, it is the position of the *fixing* eye, with the signs of horizontal and torsional gaze components reversed (because of the eyes' mirror symmetry). The set of intended gaze positions for each eye can be selected from pop-up lists above the alignment charts:

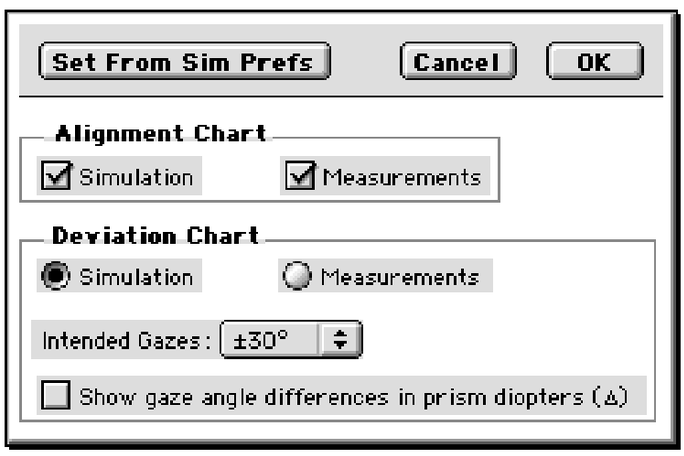


Positions of the following eye are shown as blue circles, "**o**", with connecting lines to emphasize the pattern. An arrow through each circle shows cyclorotation (torsion in excess of normal Listing's Law torsion), as tilt from straight up, multiplied by 5 for visibility. Any clinical alignment measurements you have entered are shown as red circles, "**o**", with red connecting lines. All angles are in degrees.

Window Settings & Help

At the top of the window are a *window settings button* , and a *window help button* . The window help button, you will recall, provides the present description.

Pressing gives:



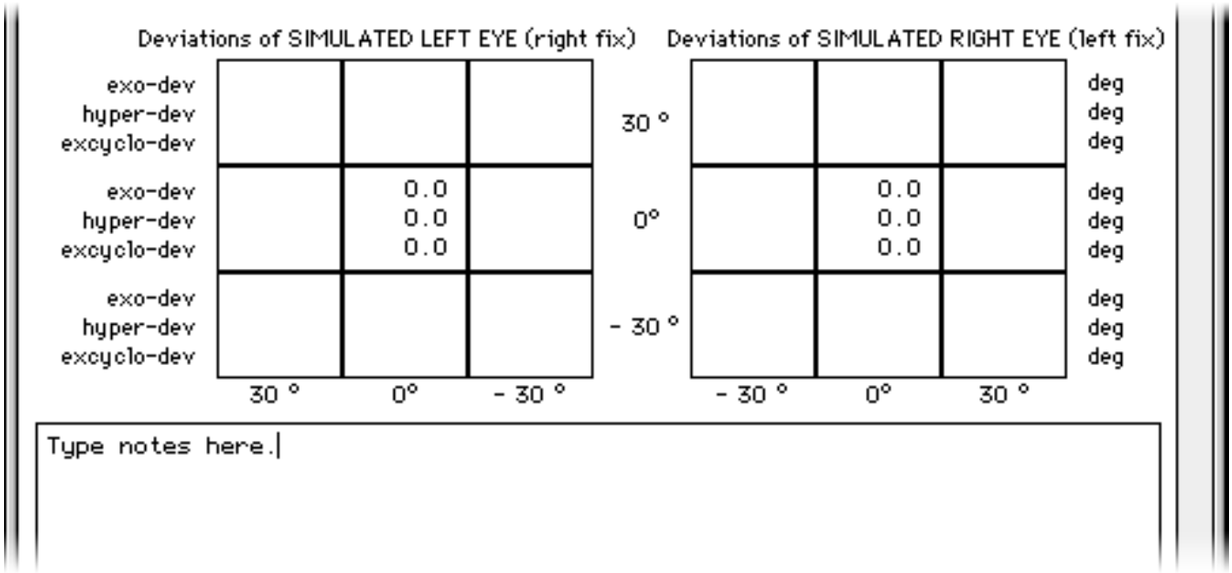
Here, we've chosen both simulation results and clinical measurements to appear in the alignment chart (as shown above).

We have also chosen to show deviations (from intended gazes) of the simulation results for ±30° intended gazes (primary position is always shown, as well).

To apply these settings and return to the Alignment Viewer, press [OK]. The new settings are temporary, in that they are associated with the current instance of the Alignment Viewer window; if you close and then reopen the Alignment Viewer, settings will revert to those given in **» Both Eyes » Preferences for Sim....** Clicking [Set From Sim Prefs] has the same effect. Press [Cancel] to undo any changes.

Deviation Chart & Notes Box

Scrolling or enlarging the Alignment Viewer reveals the *deviation chart* and the *notes box*. Each panel of the deviation chart shows the same information as the panel of the alignment chart above it, except in a different (numerical) form:



A *deviation* is a difference between following and intended gazes: positive values of *exo* mean the following eye is excessively abducted, *hyper* means it points too high, and *excyclo* means it is excessively cyclorotated such that the top of the eye has turned laterally. Labels on the right tell whether deviation units are deg or prism diopters (this is set in **» Both Eyes » Preferences**).

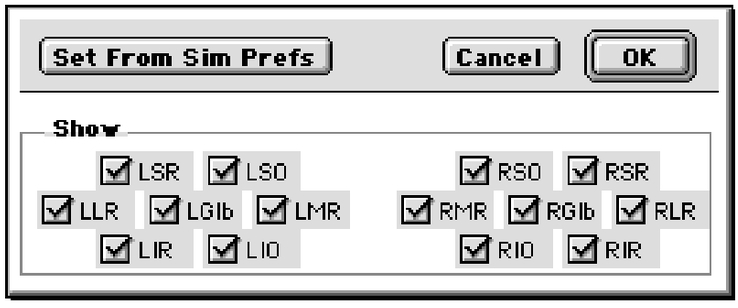
Use the *notes box* as you wish. We use it to document the simulation.

Live Eyes

The Live Eyes window provides simplified access to the most frequently used eye parameters, the only access available to Novice Users. Experienced and advanced users may prefer it to the Parameter Editor for operations like transposing an insertion, since the Live Eyes will show you if you moved in the desired direction. Also, you see immediately if the eyes responded to your manipulation as expected. If manipulations are confined to one muscle or tendon, it is easier to find the correct parameter with Live Eyes. On the other hand, if you're working with several muscles, the Parameter Editor will be more convenient.

The Live Eyes have 26 regions that produce "pop-up windows" when you click them. These regions are: the 12 tendons, the 12 muscles, and the 2 globes. A desired region can be made visible by changing Point of View or by using the *windows settings button* to hide occluding structures.

In simulating resection surgery, you may reduce a Live Eyes tendon length to zero, and then be surprised to find that a length of tendon is still shown. This is intentional, since, if a tendon disappeared, its pop-up window would become inaccessible.



Clicking the windows settings button allows you to choose which structures are shown. You can adopt previously set simulation preferences as current window settings with Set From Sim Prefs. Apply your choices to the current Live Eyes window by clicking OK, or forget them by clicking Cancel.

Live Eyes are drawn with Left Eye and Right Eye parameters, driven by Normal primary position innervations. This allows the Live Eyes to be drawn, regardless of parameter values. Consequently, the Live Eye will now show abnormalities intrinsic to an eye, but not abnormalities mediated by abnormal innervations (eg, "secondary deviations"). Graphic Eyes, of course, show all abnormalities, where solutions can be found.

Live Eyes uses color to determine the structure clicked. If it is not responding properly, your Macintosh *color table* may have been altered. Graphics applications sometimes alter the color table, and are supposed to restore it when they quit or are put in the background, but not all do. Quitting the offending program usually solves the problem.

Parameter Editor

The Parameter Editor provides Expert Users access to all Orbit parameters, and Experienced Users access to all but some seldom-used parameters. (Novice users are restricted to the frequently used variables given in Live Eyes pop-up windows).

Extensive Balloon Help (**» Help » Show Balloons**) defines all parameters and other terms used in the Parameter Editor.

Parameter values are changed in the usual way, by selecting and editing. All non-normal values appear in red. Values altered during the current visit to the Parameter Editor are additionally marked with a red drop-shadow. Click Revert to restore these parameters to the values they had when you last left the Parameter Editor. The Normal button sets all parameters to normal eye values. The Normal field (in the upper right corner of the window) shows the normal value of the selected parameter.

Exporting Eye Parameters

The eye parameters available in the Expert Level Parameter Editor can also be saved to a text file for use with another application, such as a text editor or spreadsheet, with **» Left Eye » Export Eye Parameters** and **» Right Eye » Export Eye Parameters.**

Parameter Fitter

The Parameter Fitter allows Experienced and Expert Users to automatically optimize the fit of an Orbit *simulation* to a set of clinical *measurements* by varying selected *eye parameters*. It uses the Nelder-Mead Simplex algorithm (Press et al, 1992, *Numerical Recipes in C: The Art of Scientific Computing*, edn 2).

Open » **Both Eyes** » **Parameter Fitter** and the Parameter Editor(s) for the parameters you wish to vary. Select each parameter (drag across it, highlighting the entire field), and then drag and drop it into the lower part of the Parameter Fitter window. The parameter will expand into a line showing the eye, muscle, parameter name, initial value taken by the fitting procedure, minimum and maximum values, and the value arrived at by the fitting procedure:

Eye is "L" for left eye, "R" for right eye, or "3" for third, inner eye (the Inner Eye is briefly described above, in the *Test of Binocular Alignment* section).

Mus is "LR", "MR", "SR", "IR", "SO" or "IO".

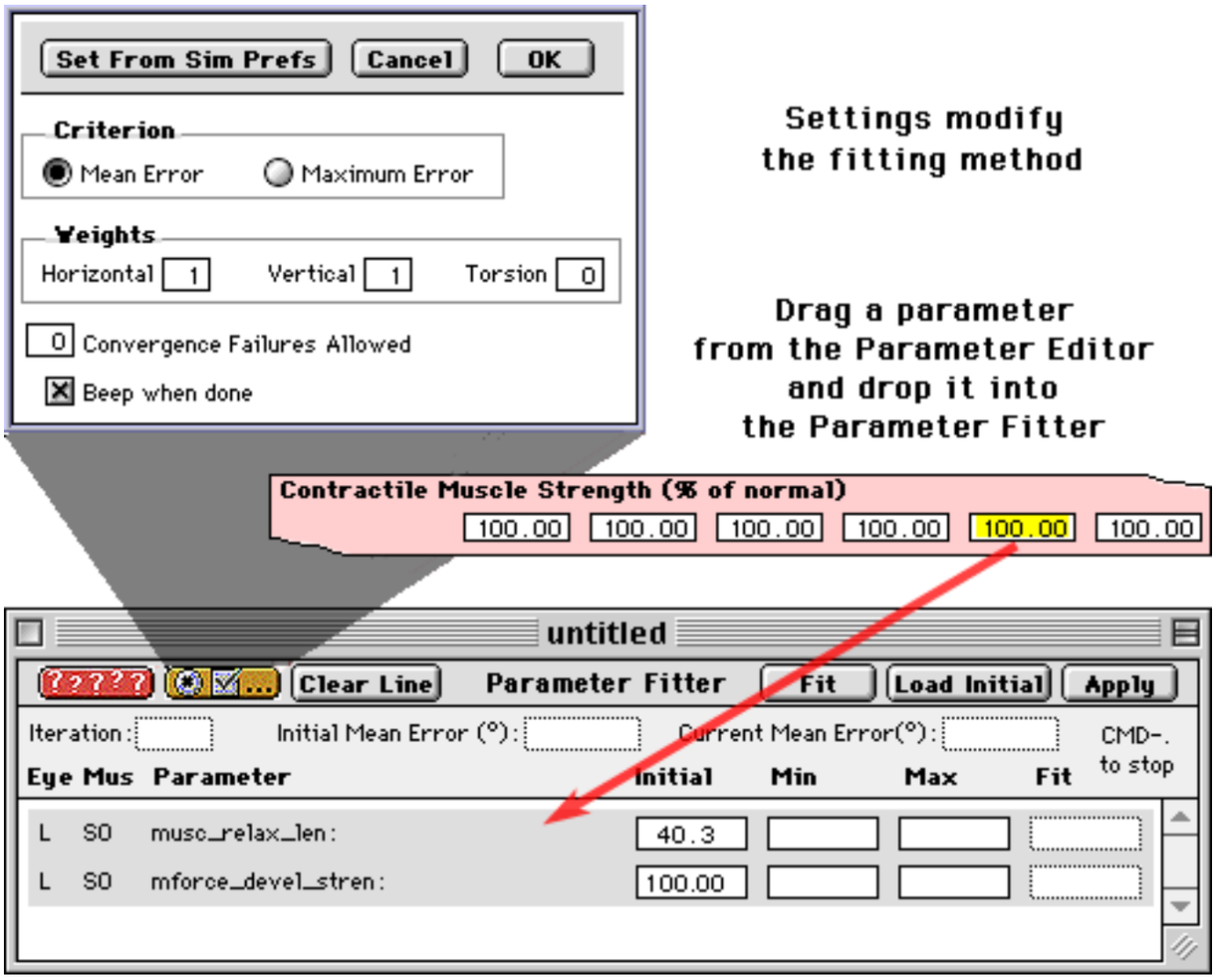
Parameter is the parameter name, as in the Parameter Editor, possibly abbreviated.

Initial is the initial value taken by the fitting procedure. It is set to the current value by default. If you have a better guess, enter it, since it is best to begin fitting with eye parameters close to those desired. The less distance in parameter space the algorithm has to traverse, the less likely it is to get trapped in a local minimum and quit with unsatisfactory parameters.

Min and **Max** are lower and upper limits on parameter values the Fitter will try. They are empty by default, meaning no limits. If the Fitter wanders into implausible values, constrain it by setting these limits. The alert "The biomechanical model could not handle the eye parameters..." means that the fitter has tried frankly illegal values (such as a negative muscle length or strength). You can dismiss the alert and fitting will continue. It might be better to set Min and Max values to keep the fitter out of trouble. A parameter's initial value will be forced to lie between the two limits.

The **Fit** field shows the parameter value arrived at by the fitting procedure. While the Fitter is running it

shows the values tried. When the Fitter is done it shows the best value found.



The **Help** button shows information similar to this Manual section.

The **Settings** button opens a window in which you can modify the fitting method:

Choose the Mean Error **Criterion** if you want the best overall fit across all gaze positions for which measurements have been entered (this might allow a few badly fitted positions). Choose the Maximum Error Criterion if you want the worst fitted position to be as good as possible.

Weights are values from 0 to 10 which determine the relative (ie: 1,1,1 is the same as 10,10,10) significance of each gaze angle component in the fitting algorithm. A weight of 0 means that the component is ignored in calculating the error that is minimized. Thus, because torsion measurements can be unreliable, its weight is set to 0 by default. If the torsion component is omitted from a measured gaze point it is, of course, omitted regardless of the weight.

It is possible for the Parameter Fitter to try eye parameters that Orbit cannot solve for some gaze angles. This may mean parameters are unrealistic, measurements are inaccurate, or Orbit is flawed. You may wish to allow a small number of such **Convergence Failures**.

Set **Beep when done** to be alerted when a fit is achieved.

Click OK to accept the settings shown for the current simulation and return to the Parameter Fitter, Cancel to abandon any changes and return, or Set From Sim Prefs to make the window show the values from Preferences.

The Fit button starts the parameter fitting algorithm. The "wait cursor" will show that Orbit is busy. As the fitter works it will show:

Iteration – the number of parameter sets tried.

Initial Mean Error (or **Initial Maximum Error**) – the fitting error for the initial parameter values. A special error value of 9999.99 means that, with the initial parameters, solutions could not be found at more points than allowed by the Convergence Failures Allowed setting. Either pick better initial parameter values, or allow more convergence failures.

Current Mean Error (or **Current Maximum Error**) – the fitting error for the current parameter values. This field updates as the algorithm works. The 9999.99 error value, meaning excessive convergence failures, is normal during fitting -- the procedure will back away from the troublesome parameter value and try something else.

Watch the **Iteration, Current Error** and **Fit** value fields to judge the algorithm's progress. If it seems to be going wrong (unbelievable parameter values), or nowhere (stuck in a "local minimum"), hold down both the ⌘ and **.** keys until the algorithm stops.

Load Initial takes corresponding values from the simulation and makes them the initial values for the fitting algorithm. This may be useful if, since initially dragging parameters to the Parameter Fitter, the simulation has been updated (eg, by previously **Apply**ing fitted values).

Apply places the fitted values into the simulation. It can be used when the fitting procedure finishes, or when it is stopped with ⌘**.** .

A multidimensional fitting routine is not guaranteed to work in every case. Some tips:

- Be sure the Fitter can get started. If Initial Error is 9999.99, one or more gaze positions cannot be solved for the initial parameters. Change an initial parameter, or look at the Alignment Viewer to find the gazes at fault. Then, either allow for that number of Convergence Failures, or remove the troublesome positions with the Intended Gaze Editor.
- It will usually improve the fit to re-run the Fitter after it claims to have found a minimum. Thus, after fitting you might click Apply, Load Initial, and Fit, to start a new search from the previously found parameters.
- You must always ask yourself: Do these parameter values make sense?

To fit *n* parameters, the Nelder-Mead Simplex algorithm works in an n-dimensional space with n+1 points (eg, a triangle for n=2, a simplex in general) which might contain the sought-for minimum. On each iteration it varies one or more parameters to learn about the local terrain, and when it has varied all parameters, guesses a new (n-dimensional) position for the worst fit point and calculates the new error. When the simplex encloses a point of relative minimum error, it tends to shrink, and when it's small enough, the algorithm quits.

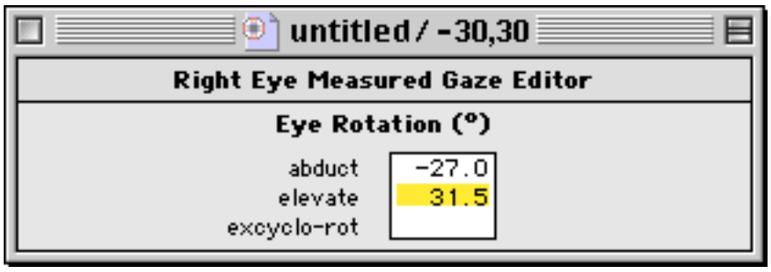
Thus, during terrain mapping, parameter values and **Current Error** will normally change and then change back. A new n-dimensional guess may increase **Current Error**, because it reflects the worst of three points (n-dimensional parameter sets), and because of poor guesses.

Measured Gaze Editor

In the SO palsy simulation, above, we imported a file of clinical measurements. It is also possible to enter clinical measurements individually from the keyboard.

To do so, select » **Right Eye** » **Measured Gaze Editor**, and choose all gaze positions for which you have data (use shift-click to select contiguous multiple items or command-click to select disjoint multiple items), and click OK.

Title bars of the Measured Gaze Editors, like those of Mechanical State Viewers are labeled with the *intended* gaze position of the following eye, that is, the position a normal following eye would have gone to. (For example, intended gaze (-30,30) corresponds to fixing eye gaze (30,30), because when the fixing eye abducts (positive) the following eye adducts (negative). If a cyclorotation is unknown, leave the **excyclo-rot** field blank (not 0).



The Expert Level Measured Gaze Editor also contains fields for eye translation, in the unlikely event that they are actually measured.

Importing Clinical Measurements

Many clinicians enter alignment measurements into spreadsheet or database programs. Most such programs can write their data as "tab-separated text", or some similar file format intended for export to other programs. Orbit can read most such files directly.

Each line in an imported file can contain the following values, in order, separated by tabs, spaces, or commas:

```
1.  intended abduction (deg)
2.  intended elevation (deg)

3.  measured abduction (deg)
4.  measured elevation (deg)
5.  measured excyclorotation(deg)

6.  measured sideways globe translation (mm)
7.  measured protruding globe translation (mm)
8.  measured upward globe translation (mm)
```

The first two fields identify each line by horizontal and vertical intended gaze positions; the remaining values are optional. If a value is unavailable, use *999* as a placeholder. It's also OK to have "short" lines, which omit trailing values (eg: globe translation and extorsion are rarely measured, so the last 3 values will usually be omitted).

So that it can read files that contain other text besides the data, Orbit ignores: lines beginning with the following three characters: **# ; >** (so, these characters can be used to introduce comment lines), tabs and spaces at the beginning of a line (allowing indentation), and all characters that are not digits, +, -, or . (so, numbers must not be expressed in scientific or engineering notation).

Recall that *excyclorotation*, as in field 5, is abnormal extorsion, extorsion beyond that expected from Listing's Law. For eyes that obey Listing's Law (eg, normal eyes), excyclorotation will always be zero.

Here is an example of a valid import file:

```
# Generic LR Palsy PreOp
# measurements for
# Orbit™ 1.8 tutorial
#
# Intended     Following Eye
# Ad    Up     Ab   Up  Excy
#
  -30   -15    -37  -14    0
  -30     0    -37    0    0
  -30    15    -38   13    0
  -15   -30    -27  -28    0
  -15   -15    -26  -14    0
  -15     0    -25    0    0
  -15    15    -26   13    0
  -15    30    -26   27    0
    0   -30    -17  -29    0
    0   -15    -16  -15    0
    0     0    -16    0    0
    0    15    -17   14    0
    0    30    -16   28    0
   15   -30    -11  -30    0
   15   -15     -9  -16    0
   15     0    -10    0    0
   15    15    -10   14    0
   15    30    -10   28    0
   30   -15     -8  -17    0
   30     0     -8   -1    0
   30    15     -9   15    0
```

Exporting Measurements & Simulated positions

If you have imported clinical measurements, or entered or modified clinical measurements using the Measured Gaze Editor you may want to write them to a text file for use with another application, such as a text editor or spreadsheet. To write measurements to a file use **» Left Eye » Export Measurements** or **» Right Eye » Export Measurements.**

It may also be useful to write simulated gaze positions to a text file. Use **» Left Eye » Export Simulation** or **» Right Eye » Export Simulation.**

(Orbit demo cannot export measurements or simulated gaze positions.)

```
 1.  intended abduction (deg)
 2.  intended elevation (deg)

 3.  measured or simulated abduction (deg)
 4.  measured or simulated elevation (deg)
 5.  measured or simulated excyclorotation(deg)

 6.  measured or simulated sideways globe translation
(mm)
 7.  measured or simulated protruding globe translation
(mm)
 8.  measured or simulated upward globe translation (mm)

 9.  measured or simulated extorsion (deg)
```

Export formats are similar to import formats (see above), with the addition of a 9th field on each line. *Measured or simulated extorsion* is included for the convenience of workers who need the 3rd Fick coordinate of measured or simulated gaze. You will recall that Field 5, excyclorotation, is not the torsion value that goes with abduction and elevation – it is abnormal torsion. Thus:

excyclorotation = extorsion – normal_extorsion

where normal_extorsion follows Listing's Law.

Clinicians, we think, will usually be interested in excyclorotation, and scientists in extorsion.

Mechanical State Viewer

The Mechanical State Viewer shows rotations, deviations, innervations, forces, and other *variables*, determined by simulation for a given gaze position. (In contrast, the Parameter Editor is used to view and edit *parameters*, values that characterize an eye and are constant across gaze positions.) The *title bar* of the Mechanical State Viewer shows the simulation name and the intended gaze position. Expert Users are shown all Orbit variables; Experienced Users are shown a reduced set. (Novice users are restricted to the eye position information in the Alignment Viewer).

The title bars of Mechanical State Viewers are labeled with the *intended gaze position* of the following eye, the eye whose variables it shows. The intended gaze position is the gaze position a normal following eye would have adopted for the corresponding fixing eye position.

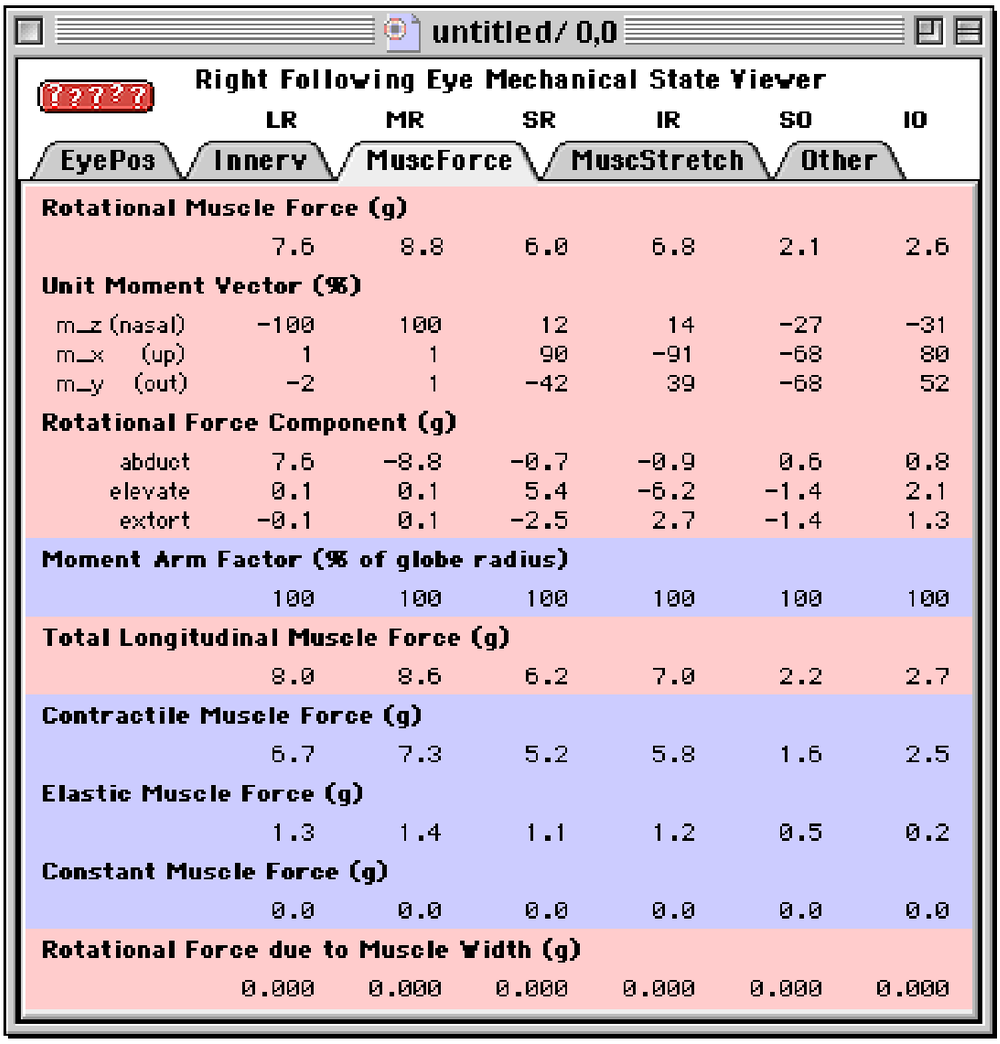
Extensive Balloon Help (**» Help » Show Balloons**) defines all variables and other terms used in the Mechanical State Viewer. Variables in the Muscle Forces Tab require some additional explanation.

Muscle Forces

The Muscle Forces Tab in the Expert Level Mechanical State Viewer is used to answer questions such as these:

- How much force does each muscle contribute to eye rotation (as contrasted with eye translation)?
- What is the axis, in Cartesian head-relative coordinates, about which a muscle rotates the eye? Researchers interested in how the brain controls eye movement need to know this instantaneous velocity axis.
- How does each muscle contribute to abduction, elevation, and extorsion? These three rotations, describe the Fick coordinate system (discussed above), familiar to clinicians.
- Has a muscle lost tangency with the globe? Is it now expending force in globe translation, at the cost of globe rotation?

- What is the total longitudinal tension in the muscle, and how much of it is due to contractile, elastic, and constant (eg, externally applied) forces.
- What forces do the muscles exert due to their sideways bending?

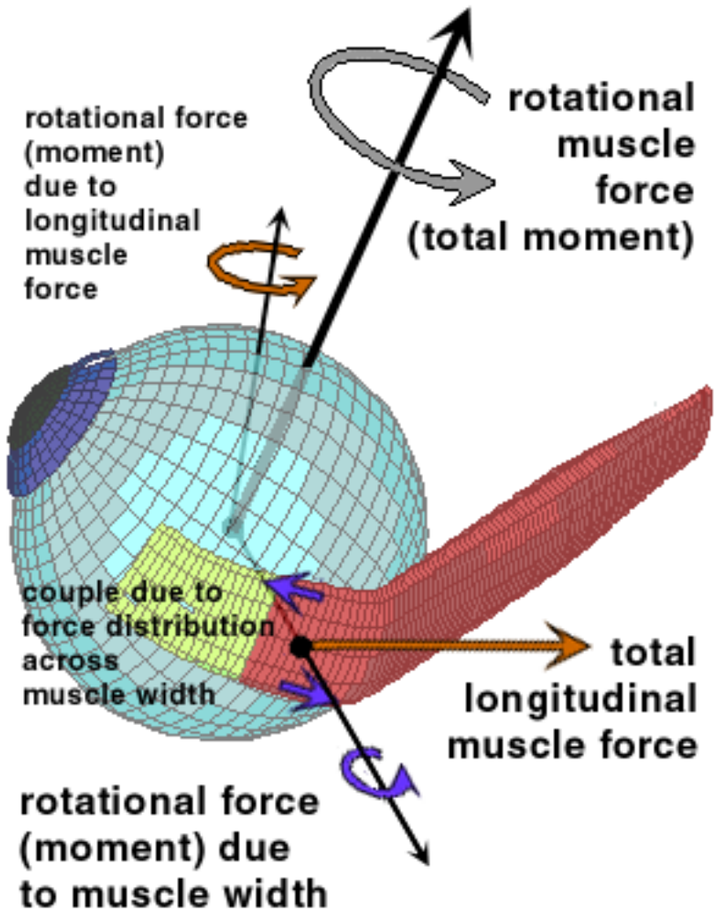

untitled/ 0,0
Right Following Eye Mechanical State Viewer
LR MR SR IR SO IO
EyePos Innerv MuscForce MuscStretch Other
Rotational Muscle Force (g)
7.6 8.8 6.0 6.8 2.1 2.6
Unit Moment Vector (%)
m_z (nasal) -100 100 12 14 -27 -31
m_x (up) 1 1 90 -91 -68 80
m_y (out) -2 1 -42 39 -68 52
Rotational Force Component (g)
abduct 7.6 -8.8 -0.7 -0.9 0.6 0.8
elevate 0.1 0.1 5.4 -6.2 -1.4 2.1
extort -0.1 0.1 -2.5 2.7 -1.4 1.3
Moment Arm Factor (% of globe radius)
100 100 100 100 100 100
Total Longitudinal Muscle Force (g)
8.0 8.6 6.2 7.0 2.2 2.7
Contractile Muscle Force (g)
6.7 7.3 5.2 5.8 1.6 2.5
Elastic Muscle Force (g)
1.3 1.4 1.1 1.2 0.5 0.2
Constant Muscle Force (g)
0.0 0.0 0.0 0.0 0.0 0.0
Rotational Force due to Muscle Width (g)
0.000 0.000 0.000 0.000 0.000 0.000

Total Longitudinal Muscle Force (g)

Total Longitudinal Muscle Force is the total force exerted by a muscle along its length, that is, in the direction of its fibers. We conceive of it as the sum of three component forces: Contractile Force, Elastic Force, and Constant Force, as described above (see section: *Muscle Force Model*).

Rotational Muscle Force (g)

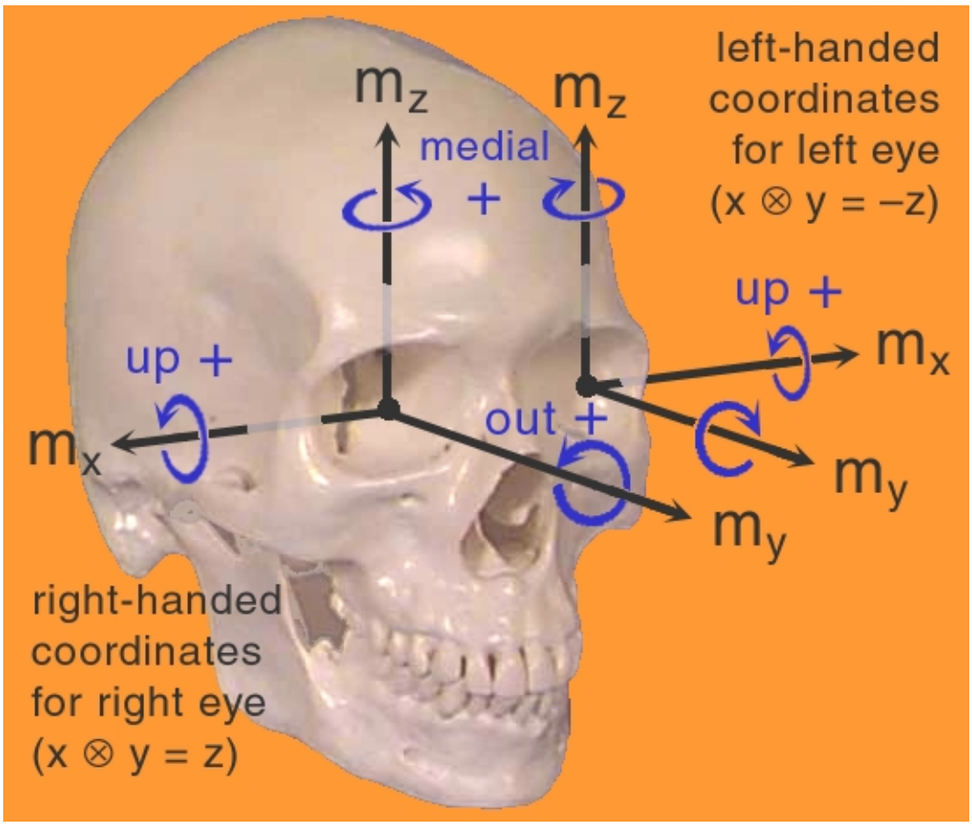
Rotational Muscle Force is the vector sum of moments due to the Total Longitudinal Muscle Force and the Rotational Force Due To Muscle Width. Both component moments reflect the local globe radius and Moment Arm Factor.


rotational force (moment) due to longitudinal muscle force
rotational muscle force (total moment)
couple due to force distribution across muscle width
total longitudinal muscle force
rotational force (moment) due to muscle width

So long as a muscle remains tangent to the globe, it will pull perpendicular to the globe radius, and exert all of its force (Moment Arm Factor = 100%) in rotating the eye. If the muscle looses tangency with the globe (Moment Arm Factor < 100%), Rotational Muscle Force is proportionally reduced.

Unit Moment Vector (%)

The Unit Moment Vector (conventionally symbolized as **m**), describes the axis about which a given muscle tends to rotate the eye. **m** is described in a Cartesian coordinate system fixed to the orbital bone (see the figure below).



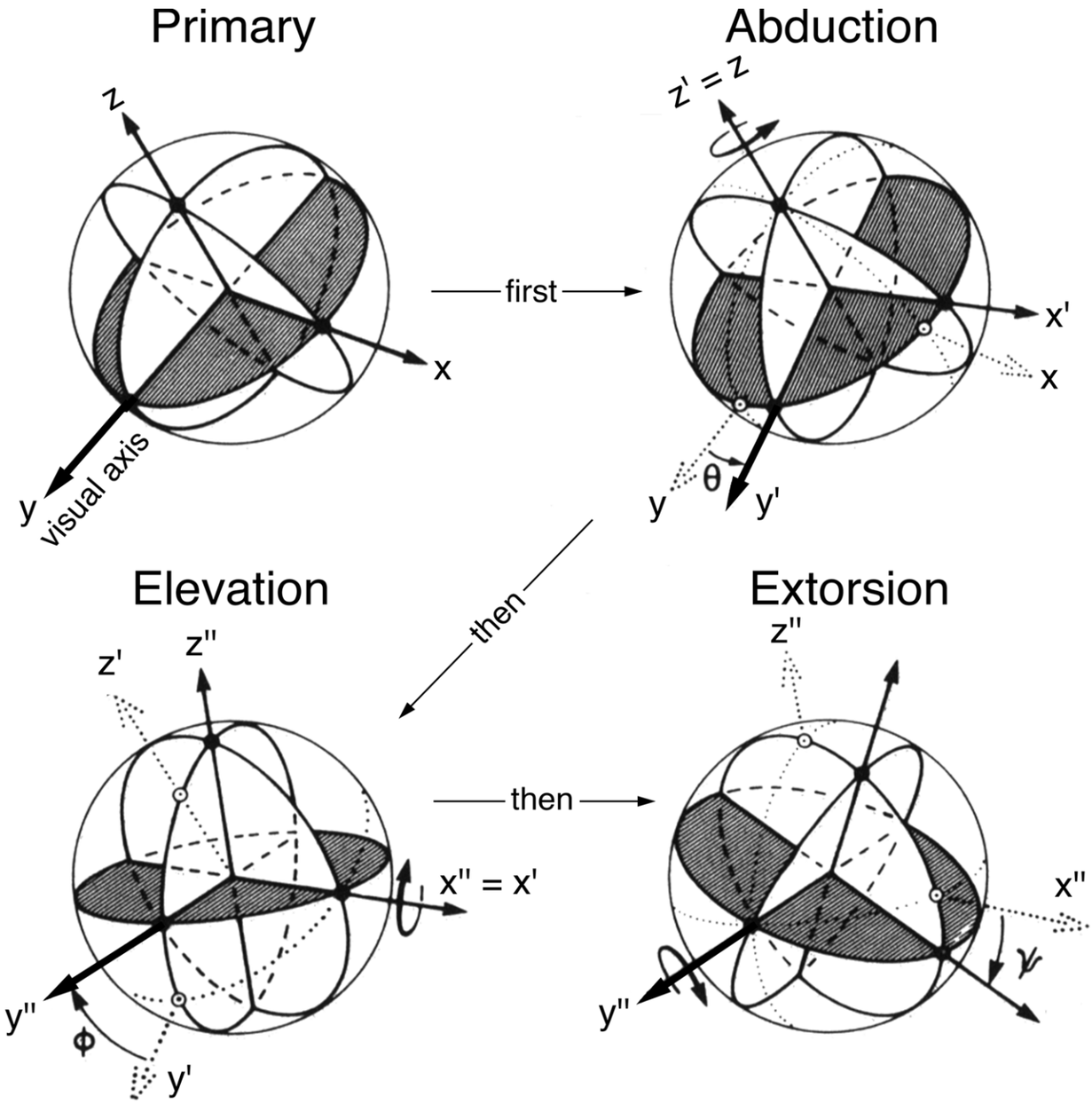
The components of **m** are shown in the figure as $\mathbf{m_X}$, $\mathbf{m_Y}$ and $\mathbf{m_Z}$. The "spin" arrows show the rotations associated with positive values of each component: $\mathbf{m_X}$ = up, $\mathbf{m_Y}$ = out, $\mathbf{m_Z}$ = medial (it would not have been correct to reuse the terms *elevate*, *extort*, and *adduct*, because they refer to components in the rotating Fick coordinate system).

$\mathbf{m_X}$, $\mathbf{m_Y}$ and $\mathbf{m_Z}$ are orthogonal vector components, so that the square root of the sum of their squares equals one, or 100%.

Rotational Force component (g)

Strabismus surgeons, who think about eye rotations in terms of the conventional Fick coordinate directions of abduction, elevation and excyclorotation, wish to know how the Total Rotational Force of a muscle acts in each direction. We call these values Rotational Force Components.

Unlike the Unit Moment Vector, Rotational Force Components are not defined in a fixed, orthogonal coordinate system: they are defined in the non-orthogonal, rotating Fick coordinate system described earlier. In consequence, abducting, elevating and excyclorotating components will not necessarily sum as vector components. Indeed component forces may be larger than the Total Rotational Muscle Force! (If this seems strange, consider the game "tug of war", in which two very large, opposing component forces yield a near zero resultant).



Regardless of how the eye arrived there, a given rotated position is specified in Fick coordinates as though the eye started in primary position, and then rotated as follows. First, the eye is imagined to rotate in abduction or adduction about the earth-vertical axis *z*. Second, it rotates in elevation or depression about *x'*, a new axis, which was not defined prior to the rotation about *z*. The axis *x'* is derived from the axis *x*, rotated

with the eye about z. Finally, cyclorotation – rotation about the visual axis – is defined about y'', which axis has rotated with the eye through the two preceding rotations.

Exporting Mechanical States

The mechanical state variables available in the Expert Level Mechanical State Viewer can also be saved to a text file for use with another application, such as a text editor or spreadsheet, with **» Left Eye » Export Mechanical State** and **» Right Eye » Export Mechanical State.**

Point of View

The Live Eyes and Graphic Eyes displays represent 3-dimensional objects on a 2-dimensional surface. To adjust how they are viewed, use **» Both Eyes » Point of View**. Novice-level users get a simplified POV Editor that allows them to select from among named points of view. Experienced and Expert Users get the complete POV Editor, which allows them to create arbitrary POVs and name them for future use with the Name It button. Named POVs can be deleted with Delete.

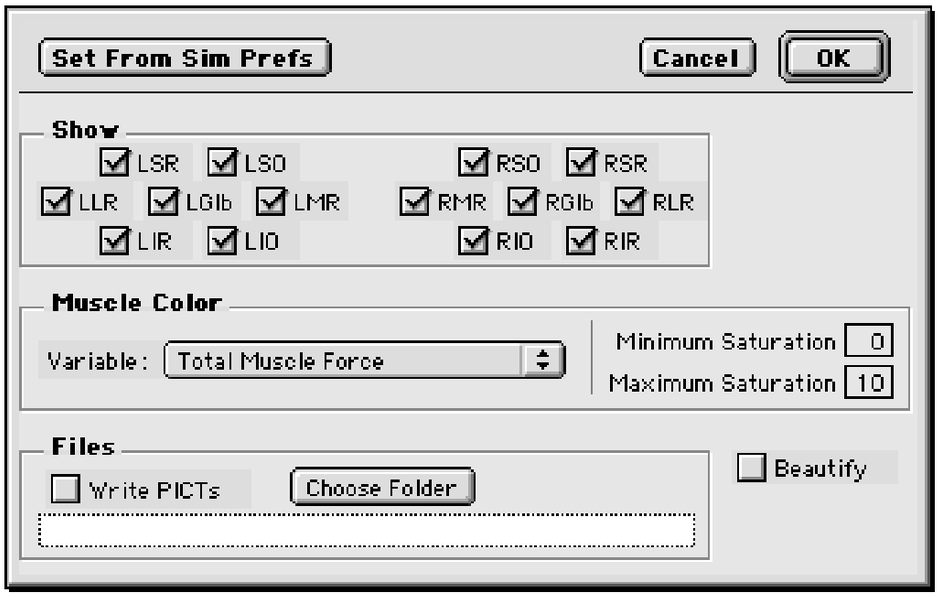
To use the complete POV Editor, imagine you are setting up a camera to take a picture of a 3-D object, and that the picture is the size of your Macintosh screen. Enter values of *Field*, *Roll*, *View From,* and *Look To*, using either the scroll bars or the numeric boxes. *Field* is the angular extent represented in the picture. *View From* is the point at which you set the camera; *Look To* is where you point it. *Roll* is rotation of the camera around the viewing axis (the line joining *View From* and *Look To*).

Press Show to see a normal eye fixing primary position, as it would appear from the current POV. When satisfied, click OK. Existing and new Live Eyes and Graphic Eyes will be shown from the new POV.

Graphic Eyes

Graphic Eyes produces a high-resolution picture of following and fixing eyes in any of the gaze positions previously selected with the Intended Gaze Selector (the Live Eyes display shows only primary position, its main purpose being access to eye parameters). Muscles are shown in red, with saturation related to one of several model variables. Select **» Left Eye » Graphic Eyes** for a representation in which the left eye is following and the right eye fixing, or **» Right Eye » Graphic Eyes** for the reverse.

The *window settings* button provides the following options:



The two groups of 7 check boxes let you chose which structures are shown. Below them is a popup list of variables than can be represented by muscle color. Choose: *total muscle force* (in grams), *contractile muscle force* (in grams), *elastic muscle force* (in grams), *stretch* (in mm, relative to relaxed length), *stretch* (as percent change from relaxed length), *or innervation* (in arbitrary units). Then set the values to be associated with minimum (gray) and maximum (pure red) muscle color saturation.

If you wish to save Graphic Eyes pictures to disk (eg, for printing), check ☑ Write PICTs. PICT files are graphics files, readable by most graphics applications. Press [Choose Folder] to determine where the files will be saved. ☑ Beautify increases the resolution of the pictures (which consequently, take longer to draw). Having checked Write PICTs, each time you create or alter a Graphic Eyes window, a PICT file will be written to the chosen folder, its name derived from the Graphic Eyes window title bar. Remember to uncheck Write PICTs when you're done saving PICTs since, otherwise, unwanted files will accumulate.

Click [Set From Sim Prefs] to adopt as current window settings the values saved in **» Both Eyes » Preferences for Sim...** Click [OK] to apply your choices to the current Live Eyes window, or [Cancel] to forget them.

Other Issues

Names

The title bar of most Orbit windows gives the name of the simulation (eg: untitled). If the window pertains to a particular intended gaze position, it too is shown in the title bar (eg: untitled/0,0).

Speed

Hardware: The hardware on which you run Orbit is the most important determinant of speed.

For comparison, we ran a simulation with normal eyes and all 289 gaze angles for one eye. All calculations shown in the flowchart shown in the section *Test of Binocular Alignment* were run by manipulating parameters in both left and right eyes.

Quadra 700	740 sec
PowerMac 6100/60	140
iMac G3/266	20
PowerBook G3/292	15
PowerMac G3/300	15

Machines with the PowerPC RISC processor (below the line) are much faster than the 680X0-based machines they replaced (above). This is because Orbit spends most of its time doing "floating point" calculations, which are a special strength of the PowerPC. Speeds for the G3 and G4 (types of PowerPCs) should vary with processor speed.

If you have a slow machine, buy enough memory so you don't have to use Virtual Memory. Turn off File Sharing. (See your Macintosh Owner's Manual for information about Virtual Memory and File Sharing).

System Software: Some INITs (software placed in the Control Panels or Extensions folders of the System Folder) can slow your Macintosh down. Experimentation can tell you if a particular INIT (or a particular combination of INITs) is exacting too high a cost. Create folders like

and

, and drag any offending INITs to them. Restart your Macintosh to run without the disabled INITs. Move them back and Restart to re-enable them. Programs called *extension managers* provide an equivalent, more convenient way, to enable and disable INITs.

Use of Orbit: If you do not have a fast machine, you will not want to use the Parameter Fitter.

Calculations are much simpler and faster if the fixing eye is normal. With a slow computer, try to work with only one abnormal eye, and to have that eye be the following eye only. That is, do not simulate "secondary" deviations.

Windows like the Parameter Editor and the Mechanical State Viewer may take a moment to open, because of the large number of fields they contain (particularly at Expert level). But there is no need to close them and re-open them for each use -- just leave them open.

The time it takes for the biomechanical model to run is proportional to the number of fixation points chosen. Use the Intended Gaze Selector to reduce the number of gaze positions to the minimum needed.

Printing

You can print Orbit windows to record patient data, intermediate simulation stages, or simulation results. We find it most useful to print the Alignment Viewer, which contains patient and simulation identifiers, alignment measurements, simulation results, and notes.

To print the Alignment Viewer, select it and then select **» File » Print...** . This request elicits the usual Macintosh Print Dialog, allowing you to choose the pages to print, the number of copies, and other options.

Parameter Editors and Mechanical State Viewers cannot be printed in this way. Instead, use the Export commands (eg: **» Left Eye » Export Eye Parameters)** to create a text file, and then edit and print the file as desired with a text processing or spreadsheet program.

Graphic Eyes are also not printed with **» File » Print...** . Instead, use the "Write PICTs" option in Preferences or Window Settings. This will create a PICT file in the

folder you choose for the current Graphic Eye (if you set the flag in Window Settings) or for every Graphic Eye you create (if you set it in Preferences). PICT format files are viewable with many applications, such as SimpleText, which came with your Macintosh, or with any graphics application that works with PICT files.

Pop-up windows are not printable, but the same information can be printed more compactly from the Parameter Editor.

All the help windows available on the Menu Bar can be printed. Some will be "paginated" in an ugly way (sorry).

Before printing, depending on how your Macintosh is set up, you may need to use » » **Chooser** to choose a printer. See your Macintosh User's Guide.

Shortcuts

Close Windows in the Background: The usual way to close a window in the background is to activate it (ie, bring it to the foreground) and click the *close box* or type ⌘W. Activating a window means waiting for it to update and redraw. To avoid the delay, hold down the *option* key and select the window on the Menu Bar, eg:

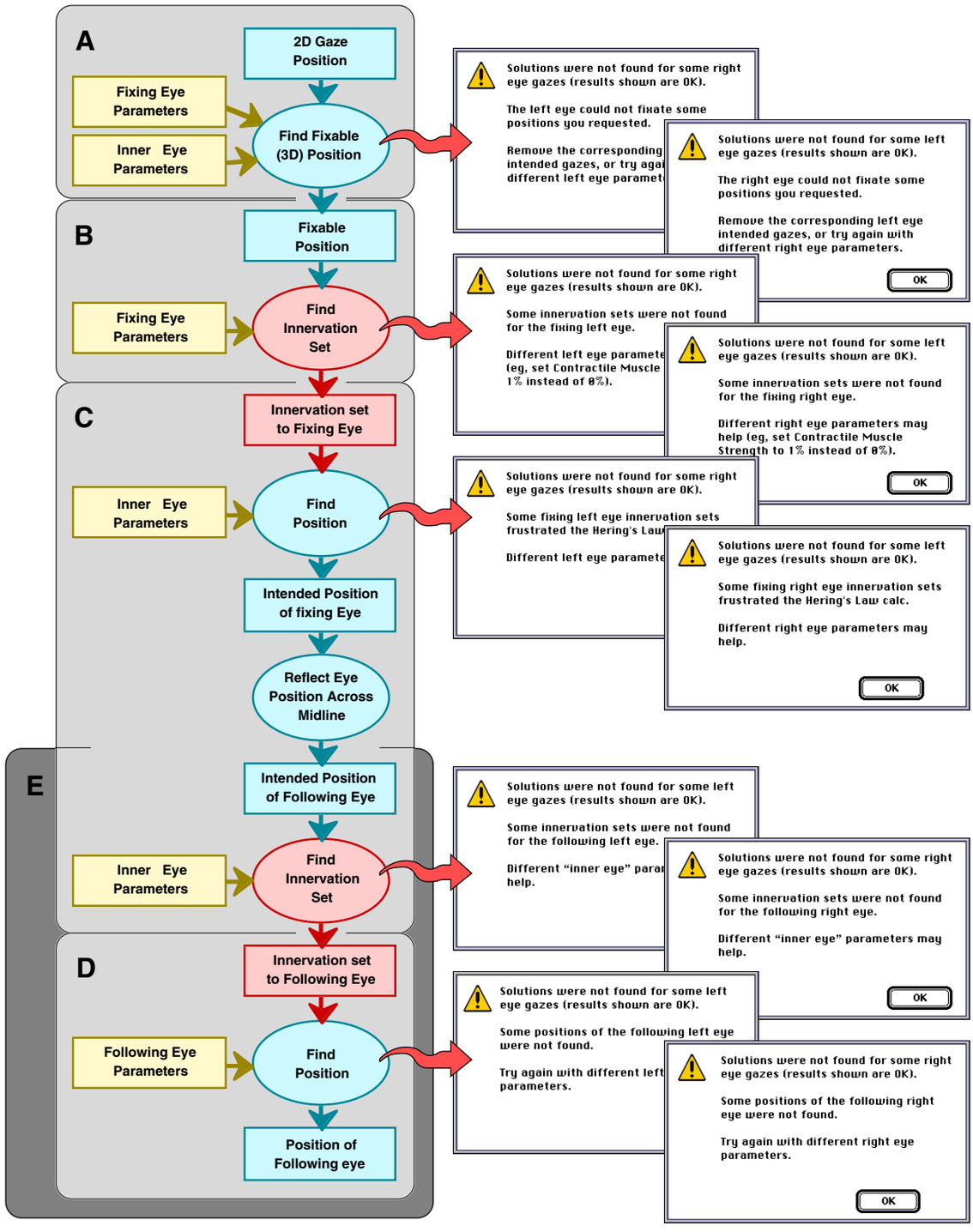
Quickly Print a Window: Wherever you can use » **File** » **Print...**, you can also use » **File** » **Print One**. The difference is that the second request does not offer any options, and just quickly prints one copy of the entire selected window.

Trouble

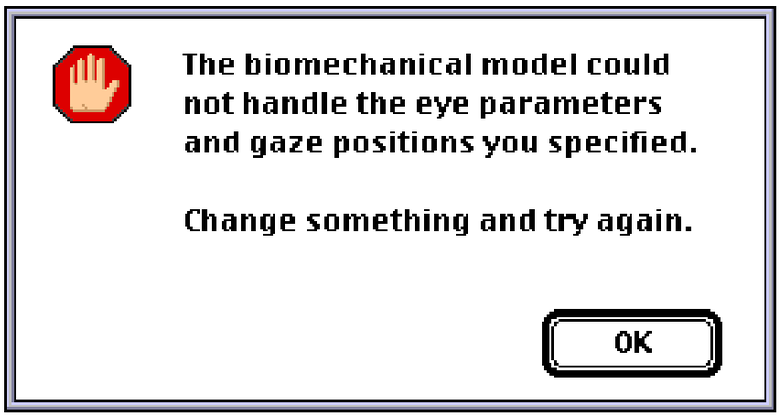
Solutions Could Not Be Found...

Orbit may fail to converge on a solution. This may be because you have chosen unrealistic parameters (check for a typo or try a value closer to Normal), extreme gaze positions, or because of limitations in the solution methods we use. Alerts suggest how to solve the various kinds of convergence problem. The figure below shows the stage of calculation that can produce each alert:

Orbit™ 1.8 Binocular Model with Possible Alerts


A
2D Gaze Position
Fixing Eye Parameters
Inner Eye Parameters
Find Fixable (3D) Position
B
Fixable Position
Fixing Eye Parameters
Find Innervation Set
C
Innervation set to Fixing Eye
Inner Eye Parameters
Find Position
Intended Position of fixing Eye
Reflect Eye Position Across Midline
E
Intended Position of Following Eye
Inner Eye Parameters
Find Innervation Set
D
Innervation set to Following Eye
Following Eye Parameters
Find Position
Position of Following eye
Solutions were not found for some right eye gazes (results shown are OK).
The left eye could not fixate some positions you requested.
Remove the corresponding
intended gazes, or try agai
different left eye paramet
Solutions were not found for some left eye gazes (results shown are OK).
The right eye could not fixate some positions you requested.
Remove the corresponding left eye intended gazes, or try again with different right eye parameters.
OK
Solutions were not found for some right eye gazes (results shown are OK).
Some innervation sets were not found for the fixing left eye.
Different left eye paramete
(eg, set Contractile Muscle
1% instead of 0%).
Solutions were not found for some left eye gazes (results shown are OK).
Some innervation sets were not found for the fixing right eye.
Different right eye parameters may help (eg, set Contractile Muscle Strength to 1% instead of 0%).
OK
Solutions were not found for some right eye gazes (results shown are OK).
Some fixing left eye innervation sets frustrated the Hering's Law
Different left eye paramete
Solutions were not found for some left eye gazes (results shown are OK).
Some fixing right eye innervation sets frustrated the Hering's Law calc.
Different right eye parameters may help.
OK
Solutions were not found for some left eye gazes (results shown are OK).
Some innervation sets were not found for the following left eye.
Different "inner eye" para
help.
Solutions were not found for some right eye gazes (results shown are OK).
Some innervation sets were not found for the following right eye.
Different "inner eye" parameters may help.
OK
Solutions were not found for some left eye gazes (results shown are OK).
Some positions of the following left eye were not found.
Try again with different left
parameters.
Solutions were not found for some right eye gazes (results shown are OK).
Some positions of the following right eye were not found.
Try again with different right eye parameters.
OK

Another type of alert means that an unacceptable eye parameter was entered, or the biomechanical model attempted a mathematically improper operation (like dividing by 0). Accumulated rounding errors and, of course programming errors, can cause this. The following alert appears:

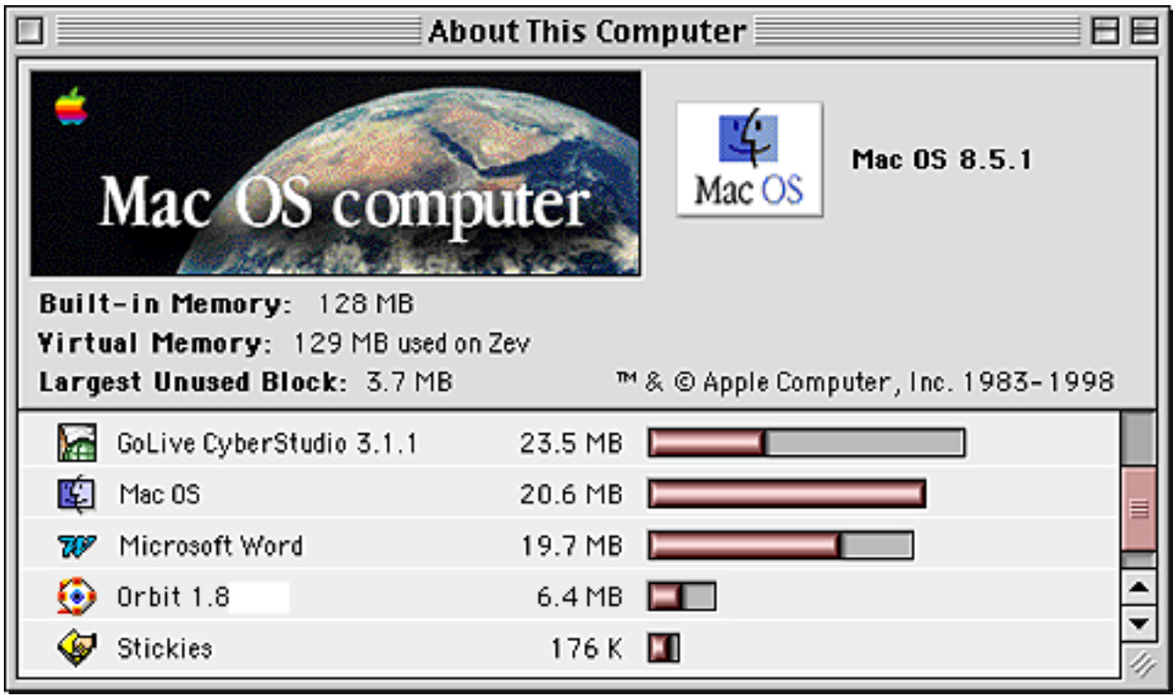

The biomechanical model could not handle the eye parameters and gaze positions you specified.
Change something and try again.
OK

Not Enough Memory

Orbit will tell you if it cannot complete a request because of insufficient memory. Here are some things to try, in the order you should try them. (A similar procedure is useful in solving memory problems with any Macintosh application):

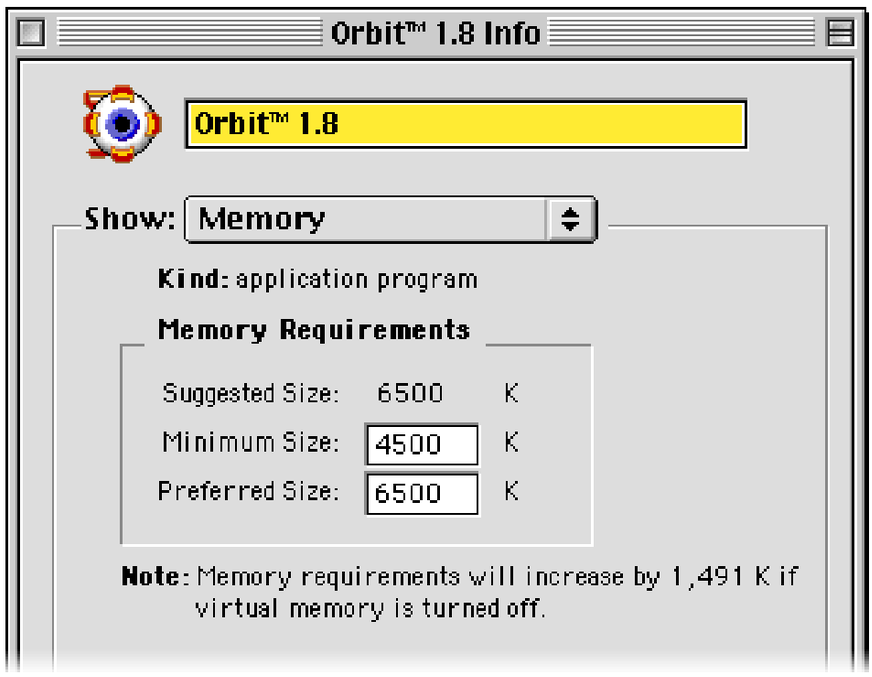
1. Close some **Orbit** windows, and try your request again.

2. Go to the Finder (eg, by clicking on the Desktop), select » » **About This Computer**, and note the size associated with Orbit. In this example Orbit got 4.8 MB when it launched:


About This Computer
Mac OS computer
Mac OS
Mac OS 8.5.1
Built-in Memory: 128 MB
Virtual Memory: 129 MB used on Zev
Largest Unused Block: 3.7 MB
™ & © Apple Computer, Inc. 1983-1998
GoLive CyberStudio 3.1.1 23.5 MB
Mac OS 20.6 MB
Microsoft Word 19.7 MB
Orbit 1.8 6.4 MB
Stickies 176 K

Quit Orbit, and (with the Orbit icon selected

), select » **File** » **Get Info**:


Orbit™ 1.8 Info
Orbit™ 1.8
Show: Memory
Kind: application program
Memory Requirements
Suggested Size: 6500 K
Minimum Size: 4500 K
Preferred Size: 6500 K
Note: Memory requirements will increase by 1,491 K if virtual memory is turned off.

As you can see from the Orbit Info window it would have preferred 6,500K, which was apparently not available when it launched. If Orbit failed to get its Preferred size of memory because other applications were also using memory when Orbit launched, quit some of the other applications and re-launch Orbit. (Because of "memory fragmentation" it might be necessary to » **Special** » **Restart** your Macintosh to make use of the freed memory!). Look at About This Macintosh. Is the Largest Unused Block large enough to meet Orbit's Preferred size? If so, launch Orbit again. If not, you may need to purchase more memory.

3. If Orbit succeeded in loading at its Preferred size, but still ran out of memory, open Orbit Info and increase Preferred size. Close the box, and try Orbit again.

4. If your basic problem is insufficient installed memory (you should have at least 8 MB available to Orbit), buy more. If you have a lot of free disk space, an easy but unattractive solution (Orbit will run slowly) is to turn on, or increase the size of Virtual Memory. Consult your Macintosh User's Guide.

Frequently Asked Questions

There will be many questions from Users about how Orbit works, how to use it, and how to cast clinical entities into its terms. We begin a "FAQ" section here, and update it in subsequent editions of this manual. Between editions, a current FAQ list will be maintained on our website at www.eidactics.com.

How do the various Preferences and Window Settings differ?

The basic difference is the "scope" or range over which the settings are effective:

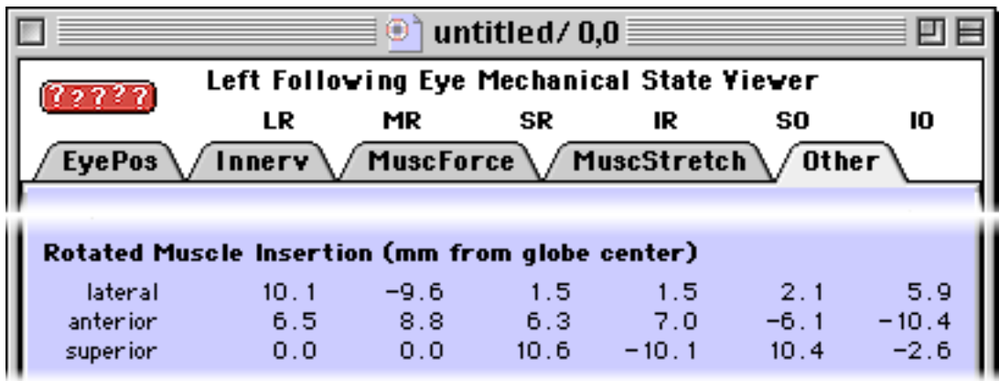
Preferences for New Simulations only affect simulations subsequently created with **» File » New**. Existing simulations whether currently open or not are unaffected. Preferences for New Simulations are stored in the special file Orbit_Prefs, which must be in the same folder as the Orbit application.

Preferences for Sim ... (where "..." is the name of the active simulation) apply to the active simulation only. When the active simulation is closed, these preferences are saved in the simulation file, and so will be in effect the next time the simulation is opened. Other simulations on disk, or open but inactive (in the background) are unaffected. Some open windows of the active simulation are also unaffected.

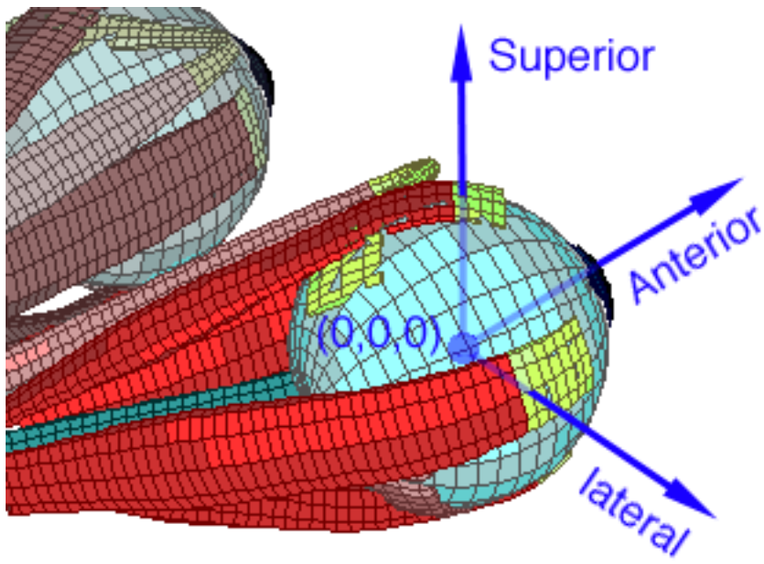
Window Settings ( ) affect only the current instance of the window containing the Window Settings button. This allows one, eg, to quickly change values displayed in an Alignment Viewer, or structures shown in a Graphic Eye, without changing anything permanently. Window Settings are lost when the window is closed, and subsequent behavior is determined by Preferences for Sim ... .

Where are normal muscle insertion coordinates?

They are in the Mechanical State Viewer:


untitled/ 0,0
Left Following Eye Mechanical State Viewer
LR MR SR IR SO IO
EyePos Innerv MuscForce MuscStretch Other
Rotated Muscle Insertion (mm from globe center)
lateral 10.1 -9.6 1.5 1.5 2.1 5.9
anterior 6.5 8.8 6.3 7.0 -6.1 -10.4
superior 0.0 0.0 10.6 -10.1 10.4 -2.6

Rotated Muscle Insertions are the centers of the insertion lines in the familiar head-fixed anatomic coordinate system, for the current gaze angles:



Usually, you will want to know insertions in primary position, as shown above (note “/0,0” in the title bar).

How do I make an Orbit Movie?

All you need to make movies yourself is Apple's "upgraded" QuickTime Movie Player, or some other utility that can read a folder of PICT files and make a QuickTime movie (Adobe Premier® is a high-end package that does this and much more).

QuickTime Movie Player came with your Mac. Launch it and look in the File menu for the "Open Image Sequence" command. If it's not there, you may need to purchase the $30 upgrade to Movie Player from Apple.

To use Movie Player to make a folder of PICS into a movie, the PICT files must all be named with the same characters followed by a positive number that tells Movie Player the order in which to string them together (eg: faden01, faden02, ...). You will probably need to rename the files produced by Orbit.

Consult the Orbit Reference section on the Graphic Eyes window to learn how to have Orbit make the required PICTs (you will need to raise your User Level to Expert).

How do I Print Orbit Windows?

Orbit's print commands are in transition, and various methods are used to print different windows. We hope to simplify things in a subsequent version.

The Alignment Viewer is printed as a picture (PICT) with **» File » Print...** . This request elicits the usual Macintosh Print Dialog, allowing you to choose the pages to print, the number of copies, and other options.

Parameter Editors and Mechanical State Viewers cannot be printed in this way (**» File » Print...** is dim). Instead, use the Export commands (eg: **» Left Eye » Export Eye Parameters)** to create a text file, and then format the file as desired with a text processing or spreadsheet program.

Graphic Eyes are printed using the "Write PICTs" option in Preferences or Window Settings. Checking this option will create a PICT file in the folder you choose for the current Graphic Eye (if you set the flag in Window Settings) or for every Graphic Eye you create (if you set it in Preferences). PICT format files are viewable with many applications, such as SimpleText, which came with your Macintosh, or with most Mac graphics applications.

Pop-up windows are not printable, but the same information can be printed more compactly from the Parameter Editor.

All the help windows available on the Menu Bar can be printed with **» File » Print..** , although some will be "paginated" in an ugly way (sorry).

When Credit is Due

Orbit™ software is © 1992–1999 Joel M Miller. You may not use any parts of Orbit in a commercial product, without permission. An early version of the computational code ("SQUINT") is in the public domain, and will be supplied on request at nominal cost. If your published work refers to Orbit or makes use of Orbit simulations, you should include a reference to the program version:

Miller, JM; Pavlovski, DS; Shamaeva, I (1999) . Orbit™ 1.8 Gaze Mechanics Simulation. Eidactics; Suite 404; 1450 Greenwich Street; San Francisco, CA 94109; USA.

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Miller, JM (1999). *Orbit*™ 1.8 *Gaze Mechanics Simulation User's Manual*. Eidactics; Suite 404; 1450 Greenwich Street; San Francisco, CA 94109; USA.

Mathematical Analyses

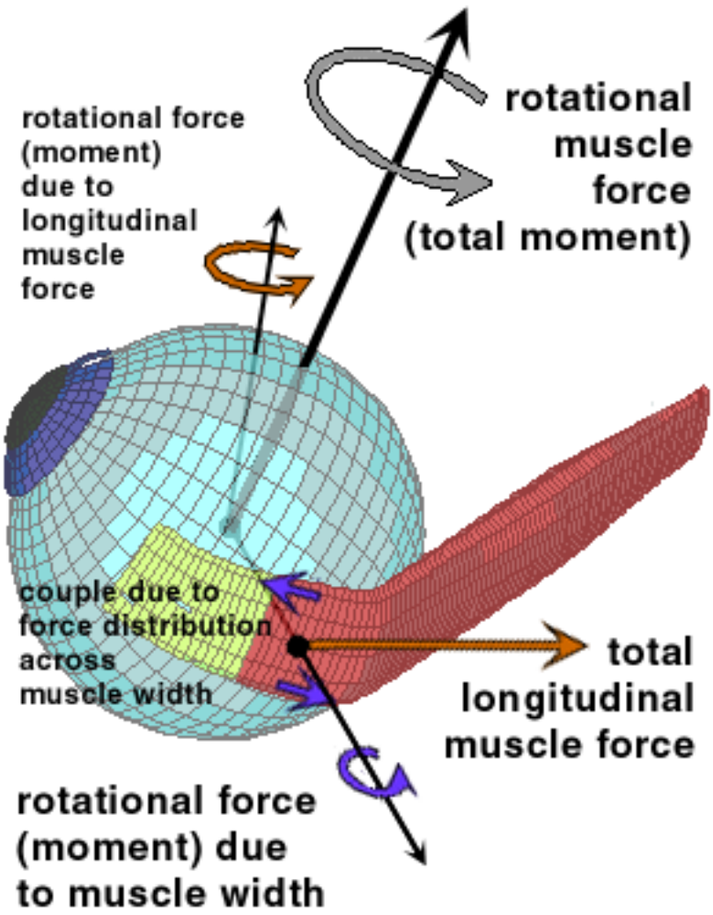
Most of Orbit's mathematical analyses are described in the literature (Robinson, 1975; Miller, 1984). Recent computational developments, however, have only been available in the source code. We will begin to describe new analyses here.

Rotational Force due to Muscle Width

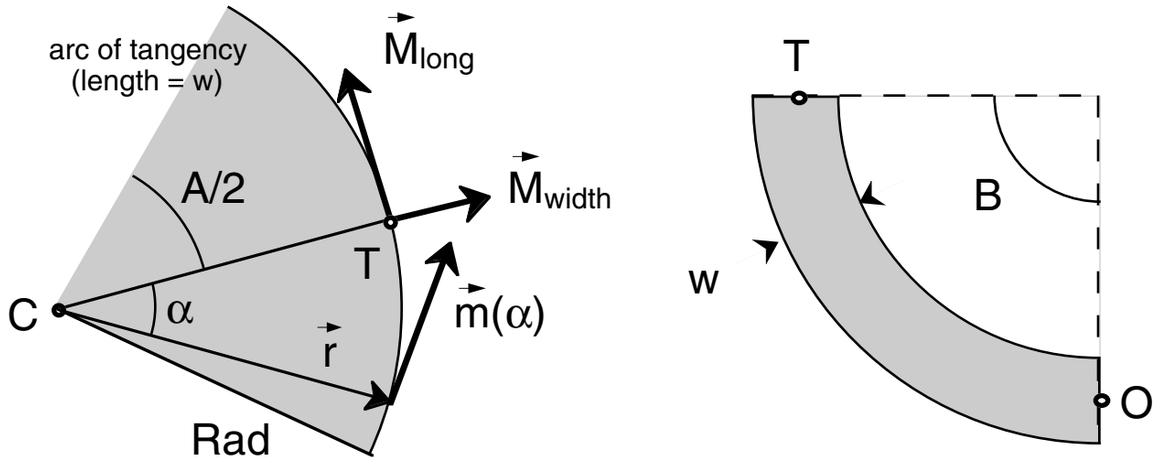
In versions prior to Orbit 1.8, the effect of nonuniform force distribution across a muscle's width was estimated with the "centroid shift" calculation described in Miller & Robinson (Miller, 1984) page 450-451. This calculation has been found to be the cause of convergence problems ("Solutions could not be found…") in certain cases.

We have, therefore replaced the centroid calculation with a different method of accounting for the force distribution across the tendon. In the new calculation, infinitesimal moments are summed across the width of the muscle. The resulting total moment is then resolved into a moment tangential to the globe (the pure "pulling" effect of the muscle applied to the center of the line of tangency), and a moment normal to the globe (the "twisting" effect of the nonuniform force distribution across the muscle.

In Orbit's terms, *rotational muscle force* (the total moment produced by a muscle on the globe) is the sum of two moments: (1) the *rotational force due to longitudinal muscle force*, which is the result of *total longitudinal muscle force* acting on the arm joining the center of rotation with the point of tangency of the muscle centerline with the globe, and (2) the *rotational force due to muscle width*, which is the result of the *couple* (pair of forces) *due to force distribution across the muscle width* acting about the axis joining the center of rotation with the point of tangency:


rotational force (moment) due to longitudinal muscle force
rotational muscle force (total moment)
couple due to force distribution across muscle width
total longitudinal muscle force
rotational force (moment) due to muscle width

The figure below left shows a section of the globe containing the *arc of tangency* of the wide muscle with the globe. The midpoint of the arc of tangency is *T*. The plane of this arc contains the globe center C and is perpendicular to the muscle path from the muscle pulley (the functional origin) to point *T*.



The muscle pulls point *T* away from us with a total longitudinal force F_{long}, which exerts a moment $\vec{M}_{long}$. The couple caused by the nonuniform distribution of force across the muscle's width (see figure above) results in a moment $\vec{M}_{width}$:

$$\vec{M}_{total} = \vec{M}_{long} + \vec{M}_{width}.$$

For a muscle of width w the angle subtended by the arc of tangency at the center of a globe of radius *Rad* is

$$A = \frac{w}{Rad}.$$

The stress of an unbent muscle is

$$s_0 = \frac{F_{long}}{w}$$

and for the fiber at angle α from the midpoint of the line of tangency:

$$s = s_0 + \frac{k}{w}\Delta L(\alpha)$$

where *k* is muscle stiffness and ΔL is the change in length of a fiber due to bending (see Miller and Robinson, 1984).

As shown in the right panel of the figure above, we estimate the effect of sideways bending of the muscle with an angle B:

$$\Delta L(\alpha) = B \cdot Rad \cdot \alpha .$$

The force $\vec{s}$ of each infinitesimal muscle fiber acts on a lever arm $\vec{r}$, producing a moment

$$\vec{m} = \vec{r} \times \vec{s} .$$

The total moment can be resolved into components due to longitudinal and width-related forces, we have:

$$M_{long} = Rad \int_{-A/2}^{A/2} \left(s_0 + \frac{k}{w} B \cdot Rad \cdot \alpha \right) \cos(\alpha) \cdot Rad \cdot d\alpha \quad (1)$$

$$M_{width} = Rad \int_{-A/2}^{A/2} \left(s_0 + \frac{k}{w} B \cdot Rad \cdot \alpha \right) \sin(\alpha) \cdot Rad \cdot d\alpha \quad (2)$$

From (1) we have

$$\begin{aligned} M_{long} &= Rad \int_{-A/2}^{A/2} \left(s_0 + \frac{k}{w} B \cdot Rad \cdot \alpha \right) \cos(\alpha) \cdot Rad \cdot d\alpha \\ &= Rad^2 \int_{-A/2}^{A/2} s_0 \cdot \cos(\alpha) \cdot d\alpha \\ &= 2 \cdot Rad^2 \cdot s_0 \cdot \sin\left(\frac{A}{2} \right) \\ &= \left(\frac{2 \cdot Rad}{w} \sin\left(\frac{w}{2 \cdot Rad} \right) \right) F_{long} \cdot Rad \end{aligned}$$

This moment is not a function of the bending angle B. It differs from the moment of Miller & Robinson (1984) by the factor $\frac{2 \cdot Rad}{w} \sin\left(\frac{w}{2 \cdot Rad} \right)$, which is close to 1 for small w.

From (2) we have

$$M_{width} = Rad \cdot \int_{-A/2}^{A/2} \left(s_0 + \frac{k}{w} B \cdot Rad \cdot \alpha \right) \sin(\alpha) \cdot Rad \cdot d\alpha$$

$$= B \cdot Rad^3 \cdot \frac{k}{w} \int_{-A/2}^{A/2} \alpha \cdot \sin(\alpha) \cdot d\alpha$$

$$= B \cdot Rad^3 \frac{k}{w} \left(\sin(\alpha) - \alpha \cdot \cos(\alpha) \right) \Big|_{-A/2}^{A/2}$$

$$= 2B \cdot Rad^3 \cdot \frac{k}{w} \left(\sin\left(\frac{w}{2 \cdot Rad} \right) - \frac{w}{2 \cdot Rad} \cos\left(\frac{w}{2 \cdot Rad} \right) \right)$$

If the muscle has lost tangency, we simply multiply the *moment due to muscle width* by the *moment arm factor*.

Annotated Orbit Bibliography

A guide to published research related to Orbit.

Current Work

Web: **www.eidactics.com**

Look here for the most current versions of Orbit software and the Orbit User's Manual, and for answers to Frequently Asked Questions about Orbit and Orbit simulations. There are also summaries of ongoing research, notices of upcoming conferences presentations, and summaries of those recently past. Feel free to create links to the site, and to suggest that other relevant sites link to it.

eMail: **jmm@eidactics.com**

Overview of Our Research Program

Miller, JM; Demer, JL (1999). Clinical Applications Of Computer Models For Strabismus. In eds Rosenbaum, A and Santiago, AP, Clinical Strabismus Management . cty Philadelphia, pub W. B. Saunders.

Introduction
- Orientation to Strabismus Models
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  - Expert systems
  - Homeomorphic models
  - Biomechanical models

Physiologic Basis
- Extraocular imaging
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Clinical Applications
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Case Studies
- Heterotopic pulleys & pattern strabismus
- Vertical rectus transposition with posterior augmentation sutures

Summary And Prospects

Bibliography

Miller JM, Demer, JL (1997). New Orbital Constraints on Eye Rotation. In eds Fetter, M, Misslisch, H and Tweed, D, Three-dimensional kinematic principles of eye, head and limb movement. cty Chur, Switzerland, pub Harwood.

The familiar notion that extraocular muscle paths are little constrained except at origins and insertions was called into question by biomechanical modeling (Miller and Demer, 1992). Magnetic resonance imaging, having previously shown that the paths of rectus muscle bellies remain fixed in the orbit during large ocular rotations (Miller, 1989), was then used to show that they remained fixed across large surgical transpositions of their insertions (Miller et al., 1993), confirming that pulleys near the globe equator couple muscle paths to the orbital wall. Autopsy and immunohistochemical studies showed that these soft rectus muscle pulleys were sleeves composed of dense bands of collagen, elastin and smooth muscle (Demer et al., 1995a), suspended from the orbit and adjacent extraocular muscle sleeves by bands of similar composition. Evidence has been found of sympathetic, parasympathetic, and nitroxidergic neurotransmission,

and innervation has been traced to the superior cervical ganglion in monkey (Demer et al., 1995b).

Muscle actions under a pulley model (Miller et al., 1995) are different from those under traditional models (Miller and Robinson, 1984; Robinson, 1975), therefore different control signals are required. The pulleys and associated tissues act, we believe, as a mid-orbital suspension, passively constraining the globe's rotational freedom to approximate Listing's Law. Tonic innervation of pulley smooth muscle stiffens musculo-orbital coupling, and perhaps pulley innervation is modulated to refine binocular coordination or move Listing's Plane.

Miller JM, Demer JL (1992). Biomechanical Analysis of Strabismus. *Binocular Vision & Eye Muscle Surgery Quarterly*, vol 7, num 4, pgs 233-248.

The mechanical elements of the eye positioning system are the globes, muscles, and various non-muscular orbital tissues. Their intrinsic complexity, variation across subjects, and obscuration by adaptive and non-mechanical factors, have made analysis far from the straightforward exercise it once seemed. Some workers have found such efforts of little interest, believing that non-mechanical factors were of overwhelming importance, or that variation across patients and surgical techniques would make any general analysis useless in individual cases. Some are uncomfortable treating a familiar discipline in unfamiliar terms.

We review efforts to construct a useful biomechanical model of binocular alignment, and the physiologic studies (of muscle paths and forces), engineering developments (muscle force measurements and computer software), and clinical research (model testing and application) spawned by modeling efforts. Although general clinical utility lies in the future, these models are already useful in special cases, in which complexity frustrates mental calculations, or in which surgeons have no relevant experience (egs: grossly abnormal orbits; prosthetic muscles). We describe how some differences among subjects may be directly measured, and how remaining differences can be estimated by "adaptive" models. Given a correct mechanical model, non-mechanical factors will be more easily isolated and studied. Finally, we describe a graphical computer program, a "software ophthalmotrope", which provides intuitive access to biomechanical strabismus models.

Biomechanical Models of Eye Alignment

Miller, JM; Pavlovski, DS; Shamaeva, I (1998). Orbit™ 1.8 Gaze Mechanics Simulation. San Francisco: Eidactics.

Orbit 1.8 is a full binocular model, meaning that both fixing and following eyes can be arbitrarily abnormal. It is no longer necessary that the fixing eye have normal, ie Listing, torsion. A new Parameter Fitter helps you choose Eye Parameters of a simulated alignment that matches clinical alignment measurements.

Miller, JM (1998). ***Orbit™ 1.8 Gaze Mechanics Simulation User's Manual.*** Eidactics; Suite 404; 1450 Greenwich Street; San Francisco, CA 94109; USA.

Miller, JM; Shamaeva, I; Pavlovski, DS (1995). Orbit™ 1.5 Gaze Mechanics Simulation. San Francisco: Eidactics.

Fixing eye can be abnormal, so long as it obeys Listing's Law, that is, has normal torsion.

Miller, JM (1995). ***Orbit™ 1.5 Gaze Mechanics Simulation User's Manual.*** Eidactics; Suite 404; 1450 Greenwich Street; San Francisco, CA 94109; USA.

Miller, JM; Shamaeva, I (1993). Orbit™ 1.0 Gaze Mechanics Simulation. San Francisco: Eidactics.

Miller, JM; Shamaeva, I (1993). ***Orbit™ 1.0 Gaze Mechanics Simulation User's Manual.*** Eidactics; Suite 404; 1450 Greenwich Street; San Francisco, CA 94109; USA.

Miller, JM; Robinson, DA (1984). A model of the mechanics of binocular alignment. *Comput Biomed Res,* vol 17, isu 5, pgs 436-470.

A computer model (SQUINT) of the static mechanics of human eyes is developed and applied to the diagnosis and treatment of defects of binocular alignment (strabismus). Brief discussions of ocular anatomy, binocular vision, strabismus and its surgical correction, and early strabismus modeling are provided for non-specialists in these areas. Models of muscle force, muscle path, globe translation, and binocularity are developed. To illustrate the use of the model in clinical cases, it is applied to the diagnosis and surgical treatment of a case of superior oblique palsy. The model's implementation under the UNIX operating system is described.

Robinson DA (1975). A quantitative analysis of extraocular muscle cooperation and squint, *Investigative Ophthalmology*, vol 14, isu 11, pgs 801-825.

The mechanical properties of human extraocular muscles have recently been described. This allows one to use the force-balance equation of mechanics to solve for the complete mechanical state of all six extraocular muscles and the passive orbital tissues in any eye position. This includes each muscle's force, length, innervation, and unit action vector, which describes how its force is distributed to act horizontally, vertically, and in torsion. Most important, this calculation method allows one to predict the tropias that occur in an eye subject to any imaginable form of peripheral pathology. It also permits, by calculation, an estimation of the correction that might be expected from any sort of muscle surgery. The tight lateral rectus syndrome is used to illustrate the application of the method in diagnosis and surgery. It also offers, for the first time, a quantitative estimate of the multitude of ways in which muscles can interact and interfere with each other when they hold the globe. Two of the results are interesting: because muscles have different lengths and sizes, their innervational participation in a movement can appear to be quite different than their mechanical participation. From an innervational standpoint, the vertical recti and obliques participate equally in vertical gaze. Muscles interfere with each other a good deal and necessitate changes of innervation to counteract these cross-couplings. This causes unexpected dependencies of innervation on eye position and leads, for example, to the fact that the superior rectus innervation in up gaze is just as large in adduction as in abduction.

Studies of Eye Muscle Forces, Paths & Pulleys

Clark, RA; Rosenbaum, AL; Demer, JL (1999). Magnetic resonance imaging after surgical transposition defines the anteroposterior location of the rectus muscle pulleys. *J AAPOS,* vol 3, isu 1, pgs 9-14.

INTRODUCTION: Connective tissue pulleys serve as the functional origins of the rectus extraocular muscles (EOMs) and constrain the sideslip of the posterior EOM bellies after transposition surgery. Anterior to the pulleys, EOM paths appreciably displace to reach their transposed insertions. The inflection points in the EOM paths from minimal posterior displacement to maximal anterior displacement should define the anteroposterior location of the EOM pulleys after transposition.

METHODS: Contiguous cross-sectional magnetic resonance images were obtained in planes perpendicular to the long axis of the orbit over its entire anteroposterior extent before and after operation in 6 patients who underwent rectus muscle transposition surgery. Four patients underwent full tendon width transposition of the vertical rectus muscles laterally for lateral rectus palsy. Two of these patients had augmentation of the transposition with sutures that fixated the temporal margins of the transposed muscles posteriorly to the sclera adjacent to the borders of the lateral rectus muscle. One patient underwent full tendon width transposition of the horizontal rectus muscles superiorly for superior rectus palsy. One patient underwent full tendon width transposition of both lateral rectus muscles inferiorly for "A" pattern esotropia. Paths of EOMs were defined relative to the area centroid of the orbit. Pulley locations were inferred from EOM paths. The postoperative change in EOM pulley location was obtained by subtracting the preoperative pulley location from the postoperative pulley location for each image plane.
RESULTS: For all patients, the postoperative change in EOM belly location was relatively small posterior to the globe-optic nerve junction. The 2 patients with abducens palsy who underwent placement of posterior augmentation sutures, however, demonstrated a significantly larger displacement of the posterior vertical rectus paths compared with similar patients who did not receive augmentation sutures. For all horizontally transposed vertical rectus muscles and inferiorly transposed lateral rectus muscles, the inflection of the EOM path began 3 mm anterior to the globe-optic nerve junction. For the superiorly transposed medial rectus muscle and lateral rectus muscle, the inflection began 6 mm anterior to the globe-optic nerve junction.

CONCLUSIONS: The anteroposterior locations of the EOM pulleys can be defined by analysis of EOM displacement after transposition surgery. Augmentation of transpositions by posterior suturing displaces the EOM pulleys substantially more than non-augmented transpositions.

Demer, JL; Miller, JM (1999). Orbital Imaging in Strabismus Surgery. In eds Rosenbaum, A and Santiago, AP, *Clinical Strabismus Management* . cty Philadelphia, pub W. B. Saunders.

Introduction
History of orbital imaging
Principles and techniques
    General principles of orbital imaging
    Technique of orbital magnetic resonance imaging (MRI)
    Technique of orbital CT
Functional anatomy of normal extraocular muscles
Some clinical applications
    Extraocular muscle paralysis
    Extraocular muscle heterotopy
    Severed and extirpated muscles
    Entrapment
    Mass effect
Summary
Bibliography

Clark, RA, M.D.; Miller, JM, Ph.D.; Demer, JL, M.D., Ph.D. (1998). Displacement of the Medial Rectus Pulley in Superior Oblique Palsy. *Investigative Ophthalmology and Visual Science,* vol 39, isu 1, pgs 207-212.

PURPOSE: The rectus extraocular muscles pass through fibromuscular connective tissue pulleys that stabilize muscle paths and control muscle pulling directions. We investigated whether abnormal forces due to superior oblique (SO) palsy can displace pulleys and muscle paths.

METHODS: Seven subjects were confirmed to have SO palsies by coronal MRI scans showing reduced SO cross-sectional area and lack of contractile change with vertical gaze change. Binocular misalignment was measured by Hess test. In those 7 palsies and in 18 normal orbits, coronal MRI scans corrected to standardized head position were analyzed to determine muscle paths in primary gaze. Horizontal and vertical pulley coordinates, known histologically to lie just posterior to the equator in primary gaze, were inferred from these muscle paths.

RESULTS: Normal pulley coordinates were very similar across normal orbits. Compared with both normal and fellow orbits, orbits with SO palsies showed a statistically significant 1.1 mm superior displacement of the medial rectus (MR) pulley. No other pulley was significantly displaced from normal. Computer simulation using the *Orbit*™ (v.1.7, Eidactics Co.) biomechanical model of ocular statics showed that, in each case, neither SO palsy alone, nor pulley heterotopy alone could account for the observed strabismus patterns.

CONCLUSION: The excyclotorsion of the globe that accompanies SO palsy does not systematically displace all rectus muscles pulleys; only the MR pulley, and so the MR path, is significantly displaced. This may be a mechanical consequence of atrophy of the adjacent SO muscle belly. Biomechanical modeling suggests that SO disfunction combined with MR pulley heterotopy better accounts for the pattern of binocular misalignment than does either mechanism alone.

Demer, JL; Poukens, V; Miller, JM; Micevych, P (1997). Innervation of extraocular pulley smooth muscle in monkeys and humans. *Invest Ophthalmol Vis Sci,* vol 38, isu 9, pgs 1774-1785.

PURPOSE: Soft pulleys stabilize paths and determine pulling directions of the extraocular muscles (EOMs). This study was conducted to characterize innervation of smooth muscles (SMs) supporting these pulleys.

METHODS: Cadaveric human and monkey orbits were step and serially sectioned for histochemical and immunohistochemical staining. Before perfusion, the superior cervical ganglia of one monkey had been injected with the anterograde tracer Phaseolus vulgaris leukoagglutinin (PHA-L). Immunoperoxidase staining to human SM alpha-actin confirmed pulley SM. Monoclonal and polyclonal antibodies were used to demonstrate PHA-L, tyrosine hydroxylase, dopamine beta-hydroxylase, phenylethanolamine-N-methyltransferase, neuronal nitric oxide synthase (NOS), and synaptophysin. The NADPH-diaphorase reaction was also used as a marker for NOS and the acetylcholinesterase (AChE) reaction for acetylcholine.

RESULTS: Pulleys, consisting of collagen and elastin sleeves supported by connective tissue containing SM, were observed around rectus muscles of humans and monkeys. The human and monkey SM was richly innervated. Axons terminating in motor end plates within SM bundles were immunoreactive to PHA-L, tyrosine hydroxylase, and dopamine beta-hydroxylase, but not phenylethanolamine-N-methyltransferase, indicating innervation of pulley SM from the superior cervical ganglion by projections using norepinephrine. Smaller axons and motor end plates were also demonstrated in SM, using NADPH-diaphorase and NOS immunoreactivity, indicating nitroxidergic innervation, and using AchE, indicating cholinergic parasympathetic innervation. The pterygopalatine and, to a lesser extent, the ciliary ganglia, but not the Edinger-Westphal nucleus, contained cells immunoreactive to NOS, suggesting that nitroxidergic innervation to pulley SM is mainly from the pterygopalatine ganglion.

CONCLUSIONS: The SM suspensions of human and monkey EOM pulleys are similar and receive rich innervation involving multiple neurotransmitters. These complex projections suggest excitatory and inhibitory control of EOM pulley SM, and support their dynamic role in ocular motility.

Clark, RA; Miller, JM; Demer, JL (1997). Location and stability of rectus muscle pulleys inferred from muscle paths.*Invest Ophthalmol Vis Sci,* vol 38, pgs 227-240.

PURPOSE: The paths of rectus extraocular muscles (EOMs) are constrained by pulleys, connective tissue sleeves mechanically coupled to the orbital walls. This study investigated, using high resolution magnetic resonance imaging (MRI), the location and stability of EOM pulleys in normal and strabismic subjects.

METHODS: Multiple contiguous coronal MRI scans spanning the anteroposterior extent of the orbit during primary gaze, upgaze, downgaze, adduction, and abduction were digitally analyzed to

determine paths of rectus EOMs. Pulley locations were inferred from EOM paths.

RESULTS: Data for ten orbits of six normal subjects established normal paths of rectus EOMs in primary gaze. Muscle paths in primary position were highly uniform across normal subjects. In secondary gaze positions, EOM paths at the level of the pulleys exhibited small but consistent shifts, relative to the orbit, opposite the direction of gaze, consistent with expected mechanical effects of intermuscular connective tissue suspensions of the pulleys. Twelve orbits of seven strabismic subjects showed, as a group, no significant difference from normal in EOM paths in primary gaze and no significant difference from normal in changes of paths of EOMs in secondary gaze positions. Two subjects with incomitant strabismus were found to have grossly abnormal EOM paths in primary gaze, suggesting heterotopic pulleys. Computer simulations of these heterotopic pulley locations accounted for the observed patterns of incomitant strabismus in both cases.

CONCLUSION: High resolution MRI can determine the location and compliance of rectus EOM pulleys. Pulley position is highly uniform across normal subjects, consistent with the notion that musculo-orbital pulleys determine pulling directions of rectus EOMs. In both normal and strabismic subjects, pulleys exhibit small shifts with eccentric gaze that are consistent with secondary intermuscular, but not musculo-global, mechanical couplings. Heterotopic pulley position is a potential cause of incomitant strabismus.

Porter, JD; Poukens, V; Baker, RS; Demer, JL (1996). Structure-function correlations in the human medial rectus extraocular muscle pulleys. *Invest Ophthalmol Vis Sci,* vol 37, isu 2, pgs 468-72.

PURPOSE. Fibroelastic pulleys function like the trochlea to fix the position and pulling direction of the recti extraocular muscles within the orbit. This study characterized the fine structure of the human medial rectus muscle pulley.

METHODS. Human medial rectus muscle pulley tissue was dissected at autopsy, immersed in aldehyde fixative solution, and processed for and examined with light and electron microscopy.

RESULTS. Pulley structure were located within posterior Tenon's fascia, closely surrounding the medial rectus muscle. Pulleys were comprised of a dense collagen matrix with alternating bands of collagen fibers precisely arranged at right angles to one another. This three-dimensional organization most likely confers high tensile strength to the pulley. Elastin fibrils were interspersed in the collagen matrix. Fibroblasts and mast cells were scattered throughout the relatively acellular and avascular collagen latticework. Connective tissue and smooth muscle bundles suspended the pulley from the periorbita. Smooth muscle was distributed in small, discrete bundles attached deeply into the dense pulley tissue.

CONCLUSIONS. Fine structural observations confirm the existence and substantial structure of a pulley system in association with the medial rectus extraocular muscle. The presence of pulleys must be considered in models of the oculomotor plant. The cytoarchitecture and placement of pulleys suggest that they are internally rigid

structures and are consistent with the idea that they determine functional origins for the extraocular muscles. However, the nature of the connective tissue-smooth muscle struts suspending the pulley system to the orbit supports the notion that the pulley position, and thus the vector force of the eye muscles, may be adjustable.

Demer, JL; Miller, JM; Poukens, V; Vinters, HV; Glasgow, BJ (1995). Evidence for fibromuscular pulleys of the recti extraocular muscles. Invest Ophthalmol Vis Sci, vol 36, isu Invest Ophthalmol Vis Sci, pgs 1125-36.

PURPOSE. Magnetic resonance imaging (MRI) shows that the paths of recti extraocular muscle (EOM) bellies remain fixed in the orbit during large ocular rotations and across large surgical transpositions of their insertions. These findings imply that recti EOMs pass through pulleys coupled to the orbit and anterior to the muscle bellies, because the insertions must move with the globe. The present study was conducted to locate anatomically and to characterize histologically the pulley tissues.

METHODS. High-resolution MRI images were collected from volunteers, using multiple gaze directions to infer the locations of, and occasionally to visualize, recti EOM pulleys. Fresh cadaver orbits were exenterated and dissected to evaluate mechanical and structural properties of the orbital connective tissues. Lipid was cleared from whole specimens to reveal tissue relationships. Other specimens were selectively step- and serial-sectioned for histochemical and immunohistochemical staining.

RESULTS. Magnetic resonance imaging demonstrated dense connective tissue structures within posterior Tenon's fascia near the equator of the globe adjacent to the recti EOMs. Histochemistry showed these structures to be pulleys--fibroelastic EOM sleeves consisting of dense bands of collagen and elastin, suspended from the orbit and adjacent EOM sleeves by bands of similar composition. A monoclonal antibody to human smooth muscle alpha-actin demonstrated substantial smooth muscle in the pulley suspensions and in posterior Tenon's fascia. Tenon's fascia itself was seen to be suspended at its periphery from the orbital walls like a drumhead.

CONCLUSIONS. The human orbit contains specialized musculofibroelastic tissues in and just posterior to Tenon's fascia that serve as compliant pulleys and determine the pulling directions of recti EOMs. In this sense, the pulleys are the functional origins of the recti EOMs and are determinants of ocular motility.

Demer, JL; Miller, JM (1995). Magnetic resonance imaging of the functional anatomy of the superior oblique muscle. *Invest Ophthalmol Vis Sci*, vol 36, isu 5, pgs 906-913.

PURPOSE. To study the size and contractile changes of the normal superior oblique (SO) muscle using high-resolution magnetic resonance imaging (MRI), and to evaluate the abnormalities in these characteristics produced by SO palsy.

METHODS. Multiple coronal MRI image planes were obtained using a surface coil to span the antero-posterior extent of each orbit and were repeated in multiple directions of gaze. Digital image analysis

was used to measure muscle cross-sectional area for evaluation of size and contractility.

RESULTS. Data for 16 orbits of 11 subjects without SO palsies established norms for morphology and contractility. On SO contraction in down gaze, maximum cross sectional area was significantly ($P < 0.001$) greater than on relaxation in up gaze, and the point of maximum cross-section shifted posteriorly with contraction. In seven subjects with clinically unilateral chronic SO palsies, the affected muscle was significantly smaller than normal ($P < 0.001$) and lacked contractile changes; clinically normal fellow SO muscles exhibited normal cross-sections and contractile changes.

CONCLUSION. High-resolution MRI, coupled with quantitative morphometric analysis, can demonstrate the size and contractility of the normal SO muscle. The technique, which can be employed using widely available clinical equipment, is also sensitive enough to detect anatomic and functional changes expected in chronic SO palsies.

Miller, JM; Demer, JL; Rosenbaum, AL (1993). Effect of transposition surgery on rectus muscle paths by magnetic resonance imaging. *Ophthalmology,* vol 100, isu 4, pgs 475-87.

PURPOSE: To evaluate effects of transposition on extraocular rectus muscle paths in middle and deep orbit.

METHODS: The effect of various transposition procedures was assessed in five patients, using surface coil magnetic resonance imaging (MRI), performed with controlled gaze before and after surgery. Path changes were compared with those expected under conventional concepts of functional orbital anatomy, quantified by biomechanical modeling.

RESULTS: Vertical rectus transpositions of 6 to 10 mm produced changes in muscle paths of 3 mm or less, assessed posterior to the equator of the globe. Lateral rectus transpositions as large as 10 mm resulted in almost no movement of muscle bellies. Conventional modeling predicted much larger changes.

CONCLUSION: The authors observed less movement of rectus muscle bellies relative to orbital walls than would be expected under the traditional assumption that transposed muscles follow the shortest path from origin to insertion. This implies that middle and deep orbital tissues (connective tissues and compartmentalized orbital fat) constrain the paths of rectus muscle bellies, preventing them from sliding freely to follow their transposed insertions. The authors propose that these tissues function as "pulleys" elastically coupled to the orbital wall, and that they are important determinants of extraocular muscle function.

Miller, JM; Robins, D (1992). Extraocular muscle forces in alert monkey. *Vision Res,* vol 32, isu 6, pgs 1099-113.

We describe an extraocular muscle (EOM) force transducer that provides low-noise signals from an alert animal for several months, is implanted without disinserting the muscle, and is well-tolerated by the body, and present results obtained with the device. The transducer can be used to study orbital statics and dynamics, and oculomotor control signals undiminished by orbital low-pass filtering

and antagonistic pairing of muscles. It may provide an index of effective EOM innervation, useful in studies of orbital tissue healing and plasticity, and oculomotor (OM) signal adaptation. During horizontal saccades transducers implanted in the lateral rectus (LR) and medial rectus (MR) of a monkey trained to fixate revealed an agonist muscle tension waveform corresponding to the "pulse-slide-step" pattern of saccadic innervation, and an antagonist waveform that was similar within a scale factor. We never observed transient increases in antagonist force at the ends of saccades (active braking) or at the beginnings. Onset of saccadic force in LR preceded that in MR by 1.6 msec for abducting saccades, and lagged that in MR by 1.1 msec for adducting saccades. During vertical saccades, transient force changes were found in LR and MR, which were likely due, at least in part, to globe translation. LR and MR forces during fixation tended to be largest with the eye about 10 degrees in elevation, and smallest in depression, indicating that effective total innervation was a function of vertical gaze, or that there was variation in the elastic component of muscle force related to orbital geometry, with LR and MR innervation independent of vertical gaze. An exponential decrease in fixation force, having a time constant of about 10 days, was observed after implantation. This may have reflected adaptive muscle lengthening or post-surgical healing.

Miller, JM (1989). Functional anatomy of normal human rectus muscles. *Vision Res,* vol 29, isu 2, pgs 223-240.

The actions of extraocular muscles depend on their positions as a function of gaze. These positions vary with muscle forces, which are normal only in alert subjects making voluntary fixations. Magnetic Resonance Imaging (MRI) was used to view normal human orbits, with voluntary gaze varied over a circular field 77 deg in dia, centered on the orbital axis. Computer-aided reconstructions, reflecting the data of four normal adult subjects, produced clear pictures of the rectus muscles and optic nerve, and yielded data on muscle paths and cross-sections. From their origins in the orbital apex to their points of tangency with the globe, rectus muscle side-slip, relative to the orbit, is approximately zero; consequently, their "muscle planes" (though not necessarily their axes of rotation) are approximately fixed in the orbit. As the rectus muscles contract they draw in towards the orbital axis, and as they relax they bow outwards; this excursion is as large as 3.7 mm. Contraction also tends to cause the planes of maximum cross-section to move posteriorly.

Miller, JM; Robins, D (1987). Extraocular muscle sideslip and orbital geometry in monkeys. *Vision Res,* vol 27, isu 3, pgs 381-92.

The belly of each extraocular muscle is elastically coupled to both the globe and orbit. The dependence of muscle planes on gaze angle must be determined experimentally. In monkeys, radio-opaque markers were implanted along the upper and lower margins of a lateral rectus. A scleral search coil was implanted in the other eye. With the eye in various gaze positions, X-ray images were made to show the LR in the lateral view. We found that as the eye rotates vertically over 50 deg (+/- 25 deg), the point of tangency of the LR with the globe slips an average of 5.1 mm vertically with respect to

the globe, allowing this point--and so the muscle plane--to remain approximately fixed relative to the orbit. The results of quantitative orbital dissections are presented in support of the sideslip calculations.

Clinical Application of Biomechanical Modeling

Clark, RA; Miller, JM; Rosenbaum, AL; Demer, JL (1998). Heterotopic muscle pulleys or oblique muscle dysfunction? *Journal of the American Association for Pediatric Ophthalmology and Strabismus,* vol 2, pgs 17-25.

INTRODUCTION: The description of connective tissue sleeves that function as pulleys for the rectus extraocular muscles (EOMs) suggests that abnormalities of EOM pulley position might provide a mechanical basis for some forms of incomitant strabismus. Pulleys determine the paths and thus the pulling directions of EOMs.

METHODS: High resolution, coronal magnetic resonance images (MRI) spanning the orbits were obtained in primary position, upgaze, and downgaze for each subject. Paths of the EOMs were measured with reference to the orbital center and permitted inference of pulley locations.

RESULTS: Data from 18 orbits of orthotropic subjects defined means and standard deviations of normal EOM pulley coordinates. Eight patients, ages 17 - 60 years, had heterotopic EOM pulleys, defined as displaced at least two standard deviations from normal. We found one to eight heterotopic pulleys (considering both orbits) in each of four patients who had been diagnosed with marked superior oblique (SO) overaction and mild to marked inferior oblique (IO) underaction. Each patient had superior mislocation of at least one lateral rectus (LR) pulley by 1.8 - 4.9 mm. Three patients diagnosed with mild to moderate IO overaction and mild to moderate SO underaction in only one orbit had one to three heterotopic EOM pulleys. Each of those patients had at least one LR pulley inferiorly dislocated by 1.9 - 4.9 mm. The final patient, who was diagnosed with mild IO underaction and normal SO function bilaterally, had bilateral superior mislocation of the medial rectus pulleys by greater than 2 mm. Computer simulations using the Orbit™ program incorporating individually measured pulley positions reproduced the clinical patterns of incomitant strabismus in all cases without postulating abnormalities of oblique muscle innervation or contractility.

CONCLUSION: Heterotopic EOM pulleys can cause patterns of incomitant strabismus that have been attributed to oblique muscle dysfunction. Even isolated mislocations of less than 2 mm, coupled with smaller mislocations of the other pulleys, can produce the clinical appearance of bilateral oblique dysfunction. Pulley heterotopy should be considered in the differential diagnosis of incomitant strabismus and oblique dysfunction.

Demer, JL; Poukens, V; A., CR; Miller, JM; Porter, JD (1998). Molecular mechanism of strabismus in Marfan syndrome: Deficient fibrillin destabilizes extraocular muscle pulleys. *Abstracts of 24th Annual Meeting of the American Association for Pediatric Ophthalmology and Strabismus*, pgs 2.

Foster, RS (1997). Vertical muscle transposition augmented with lateral fixation. *JAAPOS*, vol 1, num 1, pgs 20-30.

Demer, JL; Miller, JM; Poukens, V (1996). Surgical implications of the rectus extraocular muscle pulleys. *J Ped Ophthalmol Strabismus,* vol 33, isu 4 (July-Aug), pgs 208-218.

PURPOSE: Magnetic resonance imaging (MRI) shows that the paths of recti extraocular muscle bellies remain fixed in the orbit during large ocular rotations, and across large surgical transpositions of their insertions. This stability of muscle paths is due to their passage through pulleys which are coupled to the orbit and located anterior to the muscle bellies near the equator of the globe. Autopsy studies have shown the pulleys to be fibroelastic sleeves consisting of dense bands of collagen and elastin, suspended from the orbit and adjacent extraocular muscle sleeves by bands of similar composition. Immunohistochemical studies have revealed substantial smooth muscle in the pulley suspensions and in posterior Tenon's fascia. The pulleys function as mechanical origins of the recti extraocular muscles in the sense of determining extraocular muscle pulling directions. This study was conducted to determine the theoretical effects of the pulleys on the outcome of recti transposition surgery.

METHODS: The functional and anatomical evidence for the existence of the recti extraocular muscle pulleys was reviewed. In two patients, binocular alignment data were collected using the Hess screen test before and after vertical recti transposition surgeries for lateral rectus paralysis. Paths of the recti extraocular muscles were determined using high resolution MRI. The *Orbit '1.5* extraocular biosimulation program was employed to compute theoretical binocular alignment and muscle paths, under alternative conditions including or omitting the pulleys.

RESULTS: Pulleys are required to account for observed paths of recti extraocular muscles following transposition surgery. In the absence of pulleys, transposition of the superior and inferior recti to the lateral rectus insertion for abducens paralysis would result in bizarre ocular misalignments not observed clinically.

CONCLUSIONS: The human orbit contains specialized musculofibroelastic tissues in and just posterior to Tenon's fascia, which serve as pulleys, determining actions of recti extraocular muscles. Unimpaired pulley function is essential to effective muscle transposition surgery.

Scott, AB; Miller, JM; Collins, CC (1992). Eye muscle prosthesis. *J Pediatr Ophthalmol Strabismus,* vol 29, isu 4, pgs 216-8.

We inserted a silicone rubber elastic band along the course of a paralyzed lateral rectus and of a paralyzed superior oblique to restore alignment and to provide a spring against which the antagonist could

pull. The lateral rectus band has been in place for 7 years. It provides alignment and a field of single binocular vision of 20 degrees. The superior oblique band has been in place for 17 months. It provides alignment and single vision over 30 degrees from the primary position except for a restriction in upgaze-adduction to 25 degrees (Brown syndrome) and in downgaze-adduction to 20 degrees. Such engineered elastic bands are a useful addition to current surgical techniques for management of cases of paralysis and restriction.

Miller JM, Demer JL, et al (1990). Two mechanisms of up-shoots and down-shoots in Duane's syndrome revealed by a new magnetic resonance imaging (MRI) technique. In Campos EC (ed), *Strabismus and Ocular Motility Disorders,* London: Macmillian Press, pgs 229-234.

Spin-Offs

Dennerlein, JT; Miller, JM; Mote Jr, CD; Rempel, DM (1997). A low profile human tendon force transducer: The influence of tendon thickness on calibration. *Journal of Biomechanics,* vol 30, isu 4, pgs 395-397.

An in vitro calibration method for human tendon force transducers using tendon thickness to predict the calibration factor has been previously proposed (An et al., J. Biomechanics, 23(12), 1990). However, changes in the calibration factor due to changing tendon geometry during repeated tendon loading are unknown. A low-profile transducer design that measures tendon thickness in the transducer, in situ, is developed. An empirical model estimating the transducer's calibration factor is developed using data from in vitro tension testing of 12 fresh frozen human finger flexor tendons. Each tendon is pre-seated with ten loading cycles before data collection. Using tendon thickness, the model predicts the measured calibration factor within 0% to 15% (average 6%). During repeated loading of an in vitro tendon, the calibration factor changes 15% over the first ten cycles (0 to 50 N) due to the observed changing tendon thickness. After these first ten loading cycles the variability of the calibration factor is reduced to less than 1% for the next three loading cycles. Hence this new in vitro calibration procedures with tendon pre-seating reduces the cycle-to-cycle variability caused by the associated change in the tendon thickness.

Pfann, KD; Keller, EL; Miller, JM (1995). New models of the oculomotor mechanics based on data obtained with chronic muscle force transducers. *Ann Biomed Eng,* vol 23, isu 4, pgs 346-58.

Several phenomenological models of the oculomotor mechanics that produce saccadic eye movements have been developed. These models have been based on measurements of macroscopic muscle and orbital tissue properties and measurements of eye kinematics during saccades. We recorded the forces generated by the medial and lateral recti during saccades in an alert, behaving monkey using chronically implanted force transducers. With this new data, we tested the ability of the classic saccade models to generate realistic muscle force profiles. Errors in the predictions of the classic saccade models led to a reexamination of the current models of extraocular muscle. Both a phenomenological, Hill-type muscle model and an approximation to Huxley's molecular level muscle model based on the cross-bridge mechanism of contraction (distribution moment model) were derived and studied for monkey extraocular muscle. Simulations of the distribution moment model led to insights suggesting (i) specific modifications in the lumped force/velocity relationship in the Hill-type model that resulted in this type of phenomenological model being able to generate realistic dynamics in extraocular muscle during saccades; (ii) the distribution of activity in the different fiber types in extraocular muscle may be central to the characteristics exhibited by the muscle during saccades; (iii) the transient properties of lengthening muscle such as yielding are not

significant during saccades; and (iv) the series elastic component in active muscle may be predominantly generated by the elastic properties of the cross-bridges.

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